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Induced technological change and the attractiveness of CO_2 abatement policies

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Abstract

This paper investigates the significance of induced technological change (ITC) for the attractiveness of CO_2 abatement policies. We use analytical and numerical general equilibrium models in which technological change results from profit-maximizing investments in R&D. We show that carbon abatement policies have very different impacts on R&D across industries, and do not necessarily raise the economy-wide rate of technological progress. Focusing only on the sectors with positive R&D impacts can lead to substantial under-assessment of the GDP costs of CO_2 abatement policies. The presence of ITC implies lower costs of achieving a given abatement target, but it implies higher *gross* costs (costs before netting out environment-related benefits) of a given carbon tax. Gross costs depend importantly on the efficiency of R&D markets prior to the introduction of CO_2 policies.

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1. Introduction

It is becoming increasingly recognized that the atmospheric accumulation of greenhouse gases has the potential to produce significant changes in climate

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patterns around the globe. Faced with this possibility, researchers from a variety of disciplines have attempted to gauge both the likelihood and extent of climate change as well as the environmental and economic impacts of given changes in the world's climate. [1]

To make these assessments, analysts have developed and employed increasingly sophisticated simulation models. The models attempt to project likely environmental and economic outcomes in the absence of new policy initiatives as well as indicate how outcomes would change under policies to retard the rate of accumulation of greenhouse gases. Such policies include carbon taxes, energy efficiency standards, and subsidies to afforestation. While climate policy modeling was virtually non-existent a decade ago, [2] today many models are geared to this purpose, and the range and sophistication of the models is impressive. The first policy models tended to concentrate on the cost side of the ledger, seeking to estimate the abatement costs to the world economy or particular countries of strategies to reduce of CO_2 emissions. [3] Recently, however, there has been considerable work on assessing the economic benefits from mitigating climate change, and much progress in developing 'integrated' models—that is, models that consider simultaneously the benefits and costs of policies to reduce atmospheric accumulation of greenhouse gases. [4]

Notwithstanding their increasing sophistication, the current stock of policy evaluation tools tends to neglect a potentially important element that is relevant to both the benefits and costs of climate change policies. This element is *induced* technological change (ITC). Most of the greenhouse gas abatement policy models that incorporate technological change treat such change as *autonomous*, that is, unaffected by changes in prices brought about by policy reforms. [5] However, as several researchers recently have emphasized, [6] the rate of technological change

[1] See, for example, IPCC (1996a,b,c).

[2] Nordhaus (1980, 1982) pioneered the economic analysis of global climate policy.

[3] Examples of studies applying these first models are Edmonds and Reilly (1985), Burniaux et al. (1991), Manne and Richels (1992), Jorgenson and Wilcoxen (1996), and Böhringer and Rutherford (1997).

[4] Benefits have long been studied under the label 'climatic impact assessment' (e.g., Chen et al., 1983; National Research Council, 1983). These early studies tended to describe benefits in terms of the avoided physical, biological, or social impacts; more recent studies aim to provide economic valuations of these impacts. For a critical assessment of leading integrated climate-economy models, see Morgan and Dowlatabadi (1996), Weyant et al. (1996), and Schneider (1997).

[5] An important exception is the modeling work by Dale Jorgenson and his collaborators. Jorgenson and Wilcoxen (1996), for example, employ a model in which the rate and direction of technological progress responds to (policy-induced) changes in prices. However, in that model there is no explicit treatment of connections between policy changes, incentives to engage in R&D, and the rate of technological change. As we discuss below, such connections are important to understanding the significance of ITC for climate policy.

[6] See, in particular, Grubb et al. (1994, 1995), and Dowlatabadi (1998).

responds to policy initiatives. Climate change policies, in particular, by raising the prices of conventional, carbon-based fuels, can create economic incentives to engage in more extensive research and development (R&D) oriented toward the discovery of new production techniques that involve a reduced reliance on conventional fuels. In addition, such policies may lead to increased R&D aimed at discovering new ways to produce alternative, non-carbon-based fuels. To the extent that expanded R&D efforts bear fruit, they lead to technological progress. Thus, climate policies, R&D, and technological progress are connected: there is an induced component to technological change.

What is the significance of ITC for the attractiveness of carbon abatement? Does the possibility of ITC imply that greater amounts of carbon abatement are justified? Does it reduce the costs associated with given carbon taxes? Under what circumstances, if any, might ITC reduce to zero the cost of CO_2 abatement? Does the potential for ITC justify subsidies to research in new technologies for carbon-free sources of energy?

This paper investigates these issues. We start with a relatively simple, two-period partial equilibrium model that reveals analytically the connections between ITC and the costs of abatement policies. We then develop and employ a somewhat more complex (but still fairly compact) numerically solved general equilibrium model that enables us to explore these issues more closely.

Our investigation is in the spirit of an earlier study by Grubb et al. (1994), which to our knowledge was the first attempt to gauge the implications of ITC for climate change policy. That study applied a simple model that solves for the optimal degree of greenhouse gas abatement under alternative specifications regarding ITC. The numerical model used in the present study differs in two main ways from that of Grubb et al. First, it considers explicitly the connections between policy initiatives, the demand for and supply of R&D, and the rate of technological change. [7] Second, it employs a disaggregated general equilibrium framework in which the production decisions of various industries are identified and linked through market interactions. This allows us to explore how public policies oriented toward one industry affect R&D incentives in other industries as well as the economy-wide level of output and rate of technological progress.

This study makes two main contributions to the analysis of climate change policy. The first is methodological, and pertains to the numerical model. Although economists have long recognized the phenomenon of policy-induced innovation, [8] incorporating this phenomenon in policy models has been hampered by conceptual

[7] We concentrate on technological change that is induced from R&D activity, rather than resulting from learning-by-doing. However, as discussed in Section 4, the main insights from this analysis are also likely to apply to technological change stemming from learning-by-doing.

[8] Ahmad (1966) and Kamien and Schwartz (1968) relate the rate and direction of technological progress to changes in relative factor prices. Nordhaus (1979) offers a general treatment of the determinants of technological change.

and computational difficulties.[9] The methodological contribution of this study is the development of a consistent, disaggregated general equilibrium framework in which connections between climate policies, incentives to demand or supply knowledge-generating resources, and the rate of technological change are connected. This general equilibrium model allows for alternative specifications regarding the prior tax treatment of R&D in different industries. As indicated below, the pre-existing tax treatment of R&D influences the impacts of a new policy initiative like a carbon tax. Another important feature is the ability to consider ‘knowledge spillovers’ from a given firm’s investment in R&D. These spillovers also have an important bearing on the overall economic impacts of a new policy initiative. Although we can claim our model advances the art of environmental policy modeling, we must point out that it deals only imperfectly with some very difficult issues, including problems associated with the treatment of increasing returns to scale.[10]

The other main contribution of this study is to generate, both analytically and numerically, some qualitative insights as to how ITC affects the attractiveness of carbon abatement policies. In the presence of ITC, a carbon tax stimulates R&D and technological progress in carbon-competing industries, that is, industries that supply low- or non-carbon forms of energy.[11] The knowledge stemming from this R&D helps reduce future production costs in these industries relative to what these costs would otherwise be, other things equal. However, this does not necessarily imply that the economy-wide costs of a carbon tax are lower in the presence of ITC than they would be in a world where technological change did not respond to policy shocks. Indeed, we find that in the absence of prior distortions in R&D markets, the *gross* costs[12] of a given carbon tax in the central case are *higher* in the presence of ITC than in its absence. In the presence of ITC, the economy responds more elastically to policy shocks and undergoes greater abatement of CO_2 to a given carbon tax. The additional abatement underlies the higher gross costs of a given carbon tax in the presence of ITC. However, as we demonstrate with both of our models, this outcome can be reinforced or muted if there are prior distortions in R&D markets. These prior distortions depend on the array and magnitude of knowledge spillovers, along with the industrial allocation and scope of prior subsidies to R&D.

[9] A key problem is dealing with increasing returns to scale associated with induced technological progress, both at a conceptual level and in terms of computing equilibria. The conceptual problems alone are great enough to have generated a whole new literature on ‘endogenous growth’ (see, for example, Lucas, 1986; Romer, 1990).

[10] See Section 3.

[11] As our simulations will show, it can also stimulate additional R&D in carbon-*using* industries, where such R&D is aimed at reducing reliance on fuels whose prices are raised by the carbon tax.

[12] Gross costs are the sacrifices of GDP or consumption, before netting out the positive impacts associated with the avoidance of climate-related economic damages.

Even though the presence of ITC usually implies higher gross costs from a carbon tax, the potential *net benefits* from a carbon tax rise when ITC is present. This occurs because the higher gross costs of an appropriately scaled carbon tax are more than offset by higher gross benefits associated with more extensive carbon abatement. These results underscore the idea that, in the presence of ITC, it is crucial to consider both sides of the benefit–cost ledger in evaluating alternative carbon abatement policies.

Our focus is on qualitative insights. The analytical and numerical models' results illuminate general principles rather than suggest precise magnitudes. We cannot calibrate these models with precision because we do not know the values of key parameters defining the productivity of R&D expenditures or the extensiveness of knowledge spillovers. Nevertheless, the results obtained here are sufficiently robust to alternative parameter specifications that they suggest general principles for policy. [13]

The rest of the paper is organized as follows. Section 2 develops the analytical model and derives some key relationships between ITC and the benefits and costs of carbon abatement policies. This partial equilibrium analysis anticipates and provides intuition for the general equilibrium results obtained from the numerical model. Section 3 describes the numerical model, while Section 4 presents and interprets results from policy simulations performed with that model. Section 5 offers conclusions.

2. ITC and the costs and benefits of carbon abatement policies: a simple analytical model

This section presents a simple model that displays some of the implications of ITC for the attractiveness of carbon abatement policies. Here, we discuss the results from the model somewhat informally. The reader may refer to Appendix A for proofs of the key propositions.

A carbon emissions abatement policy can motivate both energy suppliers and energy demanders to invest in R&D. The policy can induce suppliers to find lower-cost ways of producing or delivering alternatives to fossil fuels such as biofuels or solar energy. It can also induce energy demanders (energy-using industries) to invest in the discovery of more energy-efficient processes, which would lead to reduced emissions (and tax burdens) by lowering the amount of fuel burned. For simplicity, the analytical model considers a representative energy demander (for example, an electric utility that uses carbon-based fuels to generate power). Since the tax incentive to reduce carbon emissions is fundamentally the

[13] We focus primarily on how ITC affects the overall attractiveness, rather than optimal timing, of carbon abatement policies. Ha-Duong et al. (1996), Wigley et al. (1996), Schneider and Goulder (1997), and Goulder and Mathai (1998) examine the timing issue.

same for both energy demanders and suppliers, concentrating on demanders does not change the qualitative results.

2.1. Model structure

Consider a cost-minimizing representative energy-demanding firm. [14] The model incorporates two time periods. Let E represents the total carbon emissions that the firm would produce over the two periods under business-as-usual, that is, in the absence of a carbon tax. Now, suppose a carbon tax is introduced. The firm can choose a different mix of fuels to reduce carbon emissions and thus lower its tax burden, but such switching entails a cost. In each period t ($t = 1, 2$) the cost of abatement is represented by $c(A_t, H_t)$, where abatement cost c is a function of the current level of emission abatement chosen (A_t) and the current stock of knowledge (H_t). Abatement costs are assumed to be increasing in A and decreasing in H.

First period knowledge H_1 is assumed to be exogenous, while second period knowledge H_2 is equal to first period knowledge plus the increase in knowledge that comes from first-period R&D. Thus,

$$H_2 = H_1 + a\zeta(R_1)$$

where a is an arbitrary constant and ζ is an increasing function of R&D expenditure (R). Cost-minimizing firms will undertake R&D expenditure if the reduction in future cost from increased knowledge compensates for the cost of R&D. This formulation allows for the possibility of ITC through R&D expenditure. We represent the no-ITC case by assuming that $a = 0$.

The problem for a firm facing a policy change (carbon tax) is to choose a level of abatement in each period and a level of R&D to minimize its costs over both periods. Total private costs (PC) are equal to the sum of the cost of abatement in each period, the cost of R&D (which is available at a constant price p_R) and the cost of carbon tax payments at the rate τ. Thus, the firm's problem can be represented as: [15]

$$\min_{A_1, A_2, R_1} \mathrm{PC} = c(A_1, H_1) + c(A_2, H_2) + p_R R_1 + \tau\left(\bar{E} - A_1 - A_2\right)$$

Two other key concepts require definition. The first is gross social cost, GSC, which denotes the social costs of carbon abatement without considering the environmental gains. This can be written as:

$$\mathrm{GSC} = c(A_1, H_1) + c(A_2, H_2) + \hat{p}_R R_1$$

This expression is similar to that for private cost. It includes the resource cost associated with abatement in each period plus the resource cost of R&D. It differs

[14] The representative firm approach assumes that energy use in the economy results from the demands by N identical small firms, where each firm conducts the fraction $1/N$ of all necessary abatement activities.

[15] We do not discount second-period costs. This does not affect the model's qualitative results.

from private cost in that carbon tax revenues do not appear. Although payments of carbon taxes are a cost to the firm, in this model they are not a social cost, because the revenues are assumed to have value either as publicly provided goods and services or as reductions in tax obligations. GSC also differs from PC to the extent that the (net-of-subsidy) price of R&D to firms (p_R) differs from the social cost of a unit of R&D ($\hat{p}_R$).

The other key concept is net social benefit (NSB). This represents the environmental benefit from lower carbon emissions minus gross social costs. We assume that marginal environmental damages are constant at the rate D, which means that the benefit from lower emissions is $D(A_1 + A_2)$. The expression for NSB is then:

$$\text{NSB} = D(A_1 + A_2) - c(A_1, H_1) - c(A_2, H_2) - \hat{p}_R R_1$$

In Appendix A, we prove the following four propositions.

(1) If $p_R = \hat{p}_R$, the presence of ITC lowers the gross social cost (GSC) associated with achieving a given target for emissions abatement.

(2) If $p_R = \hat{p}_R$, the presence of ITC has an analytically ambiguous effect on the gross social cost of a given carbon tax, although it implies higher gross costs under the most plausible formulations.

(3) If $p_R = \hat{p}_R$, the presence of ITC raises the net social benefits (NSB) from a given carbon tax if the carbon tax is set equal to marginal external damages from emissions.

(4) Pre-existing inefficiencies in the R&D market influence the gross costs of a carbon tax in the presence of ITC. Gross costs are lowered (raised) to the extent that is $\hat{p}_R$ less than (greater than) p_R. Differences between $\hat{p}_R$ and p_R cannot cause the gross costs to vanish, however.

2.2. A heuristic presentation of the analytical results

Fig. 1 conveys these results heuristically.[16] It depicts the schedule for the marginal cost of energy (fuel) *in period 2* for a firm that uses energy (e.g., an electric utility that uses fossil fuels). MC is the marginal abatement cost schedule for the firm if no R&D expenditure is undertaken in period 1. R&D expenditure is worthwhile only if it lowers the costs of abatement in the subsequent period by enough to compensate for the costs of undertaking the R&D. Prior R&D expenditure facilitates switching to alternatives to carbon-based fuels, and thus pivots downward the marginal cost of abatement schedule, to MC′. The schedule MC′ should be regarded as incorporating not only the incremental cost in period 2

[16] Downing and White (1986) and Palmer et al. (1995) employ a similar diagram in examining connections between technological innovation and the costs of environmental policy. The present analysis differs from these studies in focusing on carbon taxes as the mechanism for inducing innovation and in calling attention to the significance of pre-existing inefficiencies in R&D markets.

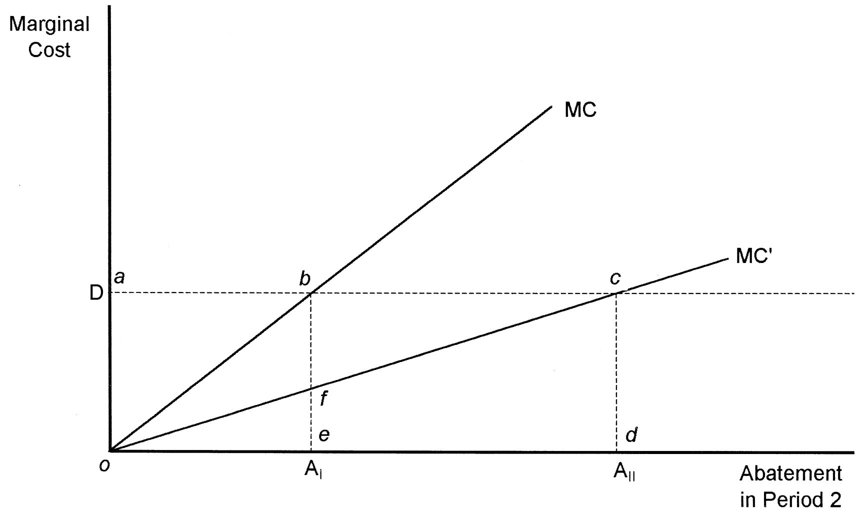

Fig. 1. ITC and the attractiveness of abatement.

of substituting alternative inputs to reduce energy use, but also the marginal cost, at each level of period-2 abatement, of the optimal increment to period-1 R&D expenditure associated with that level of abatement. If we did not include these latter costs, our analysis would effectively treat ITC—the downward pivoting of the MC schedule—as free. This would lead to overstatement of the potential gains from ITC. [17]

Fig. 1 helps illustrate the implications of ITC for the costs and benefits of abatement policies. First, note that the cost of achieving a given amount of abatement—say A_I—is lower in the presence of ITC. The area of the triangle **obe** indicates the gross costs of achieving this level of abatement if there is no ITC; the area of the smaller triangle **ofe** is the gross cost of achieving this level of abatement in the presence of ITC.

Second, note that, with the marginal cost schedules shown here, the gross abatement costs associated with a given rate of carbon tax are larger in the presence of ITC. For example, suppose the carbon tax is set at a rate equal to D, the marginal damage from emissions (marginal environmental benefit from abatement). [18] With this carbon tax, the firm responds by choosing abatement level A_{II},

[17] This heuristic discussion implicitly assumes that firms correctly anticipate the private returns from their investment expenditures. If firms systematically under- or overpredict these returns, the ex post costs of abatement (private or social) will differ from the anticipated costs, and different policy conclusions could follow.

[18] For convenience, we assume here that marginal benefits are constant. This has no bearing on the qualitative results.

which minimizes its compliance costs.[19] Gross abatement costs are given by the triangular region **ocd**. If there were no ITC, the firm's abatement costs would be the *lower* value represented by the triangular region **obe**.[20]

Finally, if the carbon tax is set equal to the marginal external damage, the net social benefits of a given carbon tax are larger in the presence of ITC. If the carbon tax is set equal to the marginal environmental damage, it leads to abatement level A_{II} in the presence of ITC and A_I in its absence. The *gross* benefits are larger in the presence of ITC: gross benefits are indicated by the rectangular region **oacd** in the presence of ITC, and by the region **oabe** if there is no ITC. Correspondingly, *net* benefits are larger with ITC: **oac**, as compared with **oab**. (However, as shown in the appendix, if the carbon tax rate is different from *D*, the presence of ITC can actually lead to lower net social benefits.)

This simple, heuristic presentation reveals some important points. First, when we talk of implications of ITC for policy costs, it is crucial to make clear whether one has in mind *the costs of an abatement target or the costs of a given carbon tax*. Second, in considering the implications for a given carbon tax, it is potentially misleading to concentrate only on the gross costs, since ITC implies higher gross (and net) benefits, as well as higher gross costs.

This presentation also implies two key points related to policy design. The first is that the presence of ITC does indeed strengthen the case for carbon abatement in the sense that it implies larger net benefits for any given specification of abatement costs, environmental benefits from abatement, and the productivity of R&D expenditure. If there is a threshold of net benefits that must be obtained before implementing an abatement policy (for example, as a result of fixed administrative costs, political costs, or distributional impacts), recognizing ITC can perhaps help greenhouse policies overcome that hurdle. The second point is that the presence of ITC does not automatically provide a rationale for a higher carbon tax. The size of the efficient carbon tax is still determined by the magnitudes of the marginal environmental benefits from abatement. If the marginal environmental benefits are constant (as in the heuristic diagram), then the optimal tax is not affected by the presence or absence of ITC.[21]

Although this analysis indicates that ITC makes a carbon tax more attractive, nothing in the analysis supports (on efficiency grounds) subsidizing R&D to exploit the possibility of inducing technological change. To justify such a subsidy,

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[19] Assume that the tax is announced in advance. The tax induces the firm to choose both the appropriate R&D expenditure (which leads to a pivoting of the MC curve) and the level of abatement.

[20] Although firms have higher abatement costs in the ITC case, the sum of abatement costs *plus tax payments* is lower in the ITC case. The extra abatement costs are **fcde−obf**, which is less than the savings in taxes given by **bcde**. The reduction in overall costs justifies the firm's prior expenditure on R&D.

[21] Goulder and Mathai (1998) examine this issue in detail, using analytical and numerical models.

one needs to adduce another source of market failure in addition to the climate-damage externality from using carbon. [22] We address this point in Section 4.

2.3. The importance of pre-existing inefficiencies in the R&D market

Firms often cannot keep private all of the knowledge obtained from their own R&D investments: such investments often produce positive knowledge spillovers to other firms. The larger these spillovers, the greater the social product from a given R&D investment. Efficiency requires that the price of R&D to firms equal the social cost of supplying R&D, which is the private cost of providing R&D services net of the external benefits from R&D services. In other words, R&D must be subsidized at a rate equal to the marginal external benefit from knowledge spillovers. In this circumstance, the private and social costs of R&D are the same: when a firm pays a dollar to enjoy additional research services, the opportunity cost to society of the resources devoted to producing R&D services will be one dollar.

Inefficiencies in R&D markets are reflected in differences between the private and social costs of R&D. The fourth proposition in the list in Section 2.1 indicates that these inefficiencies can influence in either direction the gross costs of a given carbon tax. Suppose, for example, that the R&D market is inefficient because prior subsidies to R&D in alternative fuels industries are below the level justified by large spillovers to R&D in those industries. Under these circumstances, the social opportunity cost of R&D in alternative energy ($\hat{p}_R$) is less than the net-of-subsidy price (p_R) faced by firms. If the carbon tax induces R&D by the alternative energy industries, this comes at a low cost in terms of society's resources, since the social (inclusive of spillovers) rate of return to R&D in alternative energy is especially high, even before considering implications for carbon emissions. Here the carbon tax helps undo a pre-existing inefficiency in the R&D market. In this case, the gross cost of a carbon tax will be lower than when $p_R = \hat{p}_R$. We will examine this issue further in Section 4.

3. A numerical general equilibrium model with ITC

We now present a relatively small numerically solved general equilibrium model designed to examine these issues more closely. In contrast with the previous model, this model considers the interactions among industries and allows quanti-

[22] In this connection, it is often pointed out that there is a tendency to under invest in R&D because the fruits of such investments are, to a degree, public goods that cannot be fully appropriated by the investor. The first-best policy to address such a market failure is a general R&D subsidy (wherever such spillovers apply), not a subsidy to R&D in alternative energy. Results from the numerical model support this notion. See also Schneider and Goulder (1997).

ties (including levels of R&D investment) and prices (including the prices of R&D services) to be determined endogenously. We aim to construct the simplest dynamic general equilibrium model still capable of considering the key connections between public policies and ITC. As in the previous model, the sources of ITC are R&D expenditure, which can be thought of as expenditure on 'knowledge creation'. The numerical model presented here emphasizes the importance of accounting for the opportunity costs of inducing technological change—that is, the costs of redirecting R&D resources from one sector to another—as well as the potential payoffs.

We sketch the main elements here. A complete description of the model's structure is in Appendix B.

The agents in the model are representative producers that choose levels of inputs and investment consistent with intertemporal profit maximization, and a representative household that makes consumption decisions consistent with intertemporal utility maximization. Firms' output supply, input demand and investment decisions, along with household consumption and savings decisions, determine the equilibrium time paths of industry outputs, capital stocks, and household consumption.

3.1. Production

Table 1 lists the industries and inputs in the model There are four intermediate good industries: conventional (carbon-based) energy (**EC**), alternative (non-carbon-based) energy (**EA**), carbon-intensive materials (**MI**), and non-carbon-in-

Table 1
Industries and inputs in the model

Industries
(1) Conventional energy fuels (**EC**)
(2) Alternative energy fuels (**EA**)
(3) Energy-intensive materials (**MI**)
(4) Other materials (**MN**)
(5) R&D services (***R***)
(6) Investment goods (***I***)
(7) Consumer goods (***C***)
Intermediate inputs
(1) Conventional energy fuels (EC)
(2) Alternative energy fuels (EA)
(3) Energy-intensive materials (MI)
(4) Other materials (MN)
Other inputs
(1) Knowledge capital (H)
(2) Physical capital (K)
(3) Labor (L)

tensive materials (**MN**).[23] (We use bold face to represent industry categories, and italics to denote the goods or services they provide.) By distinguishing conventional (carbon-based) energy from alternative forms of energy, we can consider how a tax on carbon influences incentives to R&D in alternative fuels industries. And by distinguishing carbon-intensive materials from other materials, we can observe how the performance of other industries might depend on the extent to which carbon fuels are a significant input into production.

The model also identifies three industries that produce the final goods or services in the model: new physical capital or investment goods (I), R&D services (R), and a general consumption good (C). R&D services, in particular, are supplied by an industry that employs labor and other inputs to generate technical information for firms in each of the other industries.[24] A key assumption of the model is that R&D services do not come free. There is a positive resource cost to such services, reflecting the education, training, and other costs that go into producing the personnel capable of offering knowledge-generating services. The underlying training costs are implied by the costs of the inputs to the R&D services industry.

In each industry, representative producers employ labor, capital, and the two types of energy and materials to produce output. We distinguish physical capital and knowledge capital. The former is expanded by investment in new physical capital. The latter is expanded by expenditure on R&D services or activities. Enlarging either capital stock allows firms to produce more output with the same amounts of other inputs.

In each industry j, a multi-level production structure generates output, X_j. The inputs into each industry are labor and the two types of energy, of materials, and of capital. Thus,

$$X_j = f_j\left(\overline{H}_j, H_j, K_j, L_j, EC_j, EA_j, MI_j, MN_j\right)$$

$$j = \mathbf{EC}, \mathbf{EA}, \mathbf{MI}, \mathbf{MN}, \mathbf{I}, \mathbf{R}, \mathbf{C} \tag{1}$$

L, K, and H refer to inputs of labor, ordinary capital, and knowledge capital, respectively. $\overline{H}_j$ represents spillover knowledge enjoyed by all firms in industry j. In contrast with H, which is appropriable knowledge, $\overline{H}$ is non-excludable. We

[23] Carbon-intensive materials are those for which carbon-based energy represents a relatively large share of input cost. See Section 3.

[24] Alternatively, one could think of firms as generating their own R&D services by devoting their own labor and other inputs to this purpose. This is equivalent to our approach, which utilizes an external R&D services industry, so long as it is assumed that the technology for generating R&D services is the same in all industries.

employ constant-elasticity-of-substitution (CES) functional forms for the production technology. Specifically:

$$X = \gamma(\overline{H})\left(\alpha_{\mathrm{H}} H^{\rho_x} + \alpha_{\mathrm{G}} G^{\rho_x}\right)^{1/\rho_x} \tag{2}$$

$$G = \left(\alpha_{\mathrm{K}} K^{\rho_{\mathrm{G}}} + \alpha_{\mathrm{L}} L^{\rho_{\mathrm{G}}} + \alpha_{\mathrm{E}} E^{\rho_{\mathrm{G}}} + \alpha_{\mathrm{M}} M^{\rho_{\mathrm{G}}}\right)^{1/\rho_{\mathrm{G}}} \tag{3}$$

$$E = \left(\alpha_{\mathrm{EC}} EC^{\rho_{\mathrm{E}}} + \alpha_{\mathrm{EA}} EA^{\rho_{\mathrm{E}}}\right)^{1/\rho_{\mathrm{E}}} \tag{4}$$

$$M = \left(\alpha_{\mathrm{MI}} MI^{\rho_{\mathrm{M}}} + \alpha_{\mathrm{MN}} MN^{\rho_{\mathrm{M}}}\right)^{1/\rho_{\mathrm{M}}} \tag{5}$$

where the industry subscript j has been suppressed for convenience, and where the α's and ρ's are parameters. ρ is related to σ, the elasticity of substitution in production: $\rho = (\sigma - 1)/\sigma$.[25]

In each industry, stocks of physical and excludable knowledge capital accumulate according to:

$$K_{t+1} = (1-\delta)K_t + I_t \tag{6}$$

$$H_{t+1} = H_t + \epsilon R_t \tag{7}$$

In the above equation, I_t and R_t respectively denote the real expenditure on new physical capital and on R&D services at time t. Expenditure on R&D underlies ITC. Just as purchases of new capital expand the stock of physical capital, purchases of R&D services augment the stock of knowledge. While physical capital depreciates at the rate δ, knowledge capital, once obtained, does not 'depreciate'. The assumption in Eq. (7) that H increases linearly with real R&D services (at a rate given by the constant ϵ) is arbitrary. For our purposes, however, the precise nature of this relationship does not matter. As we discuss below and as the sensitivity analysis confirms, the qualitative results emphasized in this paper depend on initial differences across industries in the marginal social returns to R&D expenditure. These differences depend on asymmetries in the pre-existing

[25] An alternative formulation would assume that output increases linearly with H, rather than imply diminishing returns in H (Eq. (2)). The alternative specification seems natural in some respects, but would imply increasing returns in all inputs (including H) and thus is not compatible with pure competition. Merged firms would have a cost advantage over smaller firms; the ultimate implication of this specification is monopoly production in all industries. There seems to be no way to avoid the monopoly implication without introducing a model of monopolistic competition involving differentiated products within each industry (see Smulders, 1995). Following Romer (1986), we side-step this problem by assuming diminishing returns to each factor (including knowledge) in the production function and reserving the linear knowledge–output relationship for *exogenous* spillover knowledge, as discussed below. So long as spillover knowledge is regarded as exogenous from the point of view of the individual firm, the increasing returns problem is avoided.

tax treatment of R&D and on asymmetries in spillovers, not on the assumed relationship between R and H.[26]

Given firms also enjoy spillover benefits from R&D undertaken by other firms. These knowledge spillovers enter through the element $\overline{H}$ in the scale factor γ in Eq. (2). γ is specified to be an increasing function of $\overline{H}$: spillovers imply higher output from given inputs. The spillover benefit to a representative firm in an industry depends on the industry-wide level of expenditure on R&D:

$$\overline{H}_{t+1} = \overline{H}_t + \beta \overline{R}_t \tag{8}$$

where $\overline{R}$ is industry-wide expenditure on R&D. We assume competitive production; firms regard $\overline{H}$ as exogenous. The parameter β regulates the magnitude of potential spillovers. If β is zero, $\overline{H}$ (and γ) remain constant and the production function of a given firm is unaffected by other firms' R&D expenditure.

In each industry, forward-looking firms choose levels of inputs (L, EC, EA, MI, MN) and levels of investment (I) and (R) in physical capital and knowledge capital to maximize the value of the firm (present value of profits). We assume firms have perfect-foresight expectations.[27] In making investment decisions, managers consider the benefits of their investments in terms of higher future productiveness, and weigh these benefits against the current costs of purchasing physical capital or paying for knowledge-generating services. The maximization problem for the firm is:

$$\begin{aligned} \max V_t = \sum_{s=t}^{\infty} \{ (p_s - \tau_s) [X_s - \Phi(I_s / K_s) I] - p_{\mathrm{E}s} E_s - p_{\mathrm{M}s} M_s - p_{\mathrm{L}s} L_s \\ - p_{\mathrm{I}s} I_s - (1 - \upsilon_s) p_{\mathrm{R}s} R_s \} d(t,s) \end{aligned} \tag{9}$$

In the above equation, V_t is the value of the firm at time t, and p_s is the output price at time s, p_{is} is the price of input i ($i = E, M, L, I, R$) at time s, τ_s is the per-unit tax on output, and υ_s is the *ad valorem* subsidy to R&D enjoyed by the

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[26] One can interpret Eq. (7) as representing agents' expected relationship between investments in R and the change in H. The model assumes that, *on average*, agents in each industry correctly assess this relationship. Of course, in the real world, some R&D investments will outperform expectations, and some will underperform. Eq. (7) implicitly averages out these differences. Two other points related to Eq. (7) are worth noting. First, the equation assumes no depreciation or obsolescence in H. Allowing for such obsolescence would not change the qualitative results below. Second, the contribution of R_t to knowledge is independent of the current level of knowledge, H_t. Thus, the level of knowledge does not affect the productivity or cost of investments in additional knowledge. This contrasts with a 'dynamic spillovers' formulation according to which each investment in knowledge raises the productivity or reduces the cost of future investments in knowledge. See, for example, Romer (1990) and Jones and Williams (1996).

[27] Clearly, other investment formulations are possible, and the empirical evidence on the determinants of firms' investment decisions is inconclusive. Managers of firms are assumed to be able to fathom perfectly the full economic implications of policies once they are introduced. However, the policy shocks (carbon taxes) considered in Section 4 are unanticipated.

firm. p_E and p_M, in particular, are the unit prices of the composite energy and materials inputs defined by the aggregation functions in Eqs. (4) and (5) above. $d(t,s)$ is a discounting operator defined by:

$$d(t,s) = \begin{cases} 1, & s = t \\ \prod_{v=t}^{s-1} (1 + r_s)^{-1}, & s > t \end{cases}$$

where r_s denotes the market rate of return from period s to period $s+1$. Firms maximize Eq. (9) subject to the production technology (Eqs. (2)–(5)) and the equations of motion for physical and knowledge capital (Eqs. (6)–(8)). Since we are concerned with the dynamics of the economy's response to policy changes, we include attention to adjustment costs associated with the installation or removal of physical capital. The function Φ represents adjustment costs per unit of investment in physical capital. Φ is convex in I_s/K_s, the rate of investment. R&D expenditure is assumed to involve no adjustment costs. [28] The appendix shows the conditions defining the solution to the firm's maximization problem. The convexity of the adjustment cost function implies that, following a policy change, it is optimal for firms to approach gradually the optimal long-run capital intensity of production. Thus, the approach to the long-run equilibrium is more gradual than in models in which capital can adjust without cost.

The only policy instruments in the model are taxes on output (the τ_j's) and subsidies to R&D (the v_j's). The carbon tax is modeled through τ_{EC}, the tax on the output of the fossil-based fuels industry. To keep the model as simple as possible, we do not include any other taxes or any government consumptive activities (government purchases). Whatever revenues are collected by the government are transferred in lump-sum fashion to the household.

The model tracks the use of EC through time, and from that generates a path of carbon emissions. However, this is not a fully integrated model in the sense that it does not consider explicitly the economic impacts of changes in atmospheric concentrations of CO_2.

3.2. Household behavior

The model's treatment of household behavior is very simple. A representative, infinitely-lived household with perfect foresight allocates income between saving and consumption in accordance with utility maximization. The utility function is:

$$U_t = \sum_{s=t}^{\infty} (1+\omega)^{t-s} N_s \frac{1}{\rho_U} C_s^{\rho_U} \tag{10}$$

[28] Allowing for adjustment costs in the acquisition of R&D services reduces somewhat the magnitudes of the R&D investment responses to policy changes, relative to the responses shown in results below. However, this would not change the qualitative insights. There is virtually no empirical evidence on adjustment costs associated with acquiring R&D services.

and the household sector wealth accumulation condition [29] is:

$$W_{Ft} - W_{F,t-1} = r_{t-1} W_{F,t-1} + Y_{Lt} + Y_{Gt} - p_{Ct} N_t C_t \tag{11}$$

where: U_t = intertemporal utility evaluated from time t; C_t = per-capita consumption at time t; N_t = population at time t; W_{Ft} = financial wealth (wealth from physical and knowledge capital) at time t; [30] Y_{Lt} = labor income at time t; Y_{Gt} = government transfer income at time t; p_{Ct} = price of the consumption good at time t; ω = pure rate of time preference; ρ_U = transform of intertemporal elasticity of substitution in consumption, σ_U ($\rho_U = (\rho_U - 1)/\sigma_U$).

Population is exogenous (assumed to grow at 1.25% annually), and aggregate labor supply is proportional to the current population. Labor is perfectly mobile across industries. The conditions for optimal consumption are shown in Appendix B.

3.3. Equilibrium and growth

We solve the model to obtain the general equilibrium dynamic path of the economy. This involves obtaining, in each period of time, a set of prices that clears all markets. In particular, we must solve in each period for the market-clearing values of the primary prices p_{EC}, p_{EA}, p_{MI}, p_{MN}, and r. [31] The equilibrium values for these prices assure that (1) the supply of each produced good equals its demand and that (2) firms' demands for funds (to purchase R&D services and new physical capital) equal the supply of funds from household saving. [32] The vector of equilibrium prices in a given period depends on expectations about the future, since agents are forward-looking. To obtain perfect-foresight expectations, we repeatedly solve the model forward (usually over a simulation interval of 75 years), updating expectations each time until the posited expectations match the corresponding variables that are generated by the model. This yields the dynamic path consistent with perfect-foresight expectations.

Economic growth is determined by the rates of growth of labor, of physical capital, and of knowledge. The rate of aggregate labor growth is exogenous and

[29] Recursively solving expression (10) subject to the usual transversality condition yields the household's intertemporal wealth constraint, which requires that the present value of consumption equal current financial wealth plus the present value of labor and transfer income.

[30] W_{Ft} is financial wealth at the end of period t, or, equivalently, at the beginning of period $t+1$. Income is received and consumption decisions are made at the end of the period.

[31] As indicated in the appendix, all other prices can be determined from the primary prices.

[32] The price of labor is the numeraire. By Walras's law, supply-demand balance for labor is assured when the other excess demands are zero. (We verify this is the case as a check on the model.) The capital-good-producing industry (I) and the R&D services industry (R) do not employ capital. Because these industries exhibitconstant returns to scale in all the variable inputs, we do not need to employ separate excess demand conditions for these industries, and the prices p_I and p_R can be determined directly from the prices of intermediate inputs.

constant since, as mentioned, labor supply is proportional to population, and population grows at a constant rate. The rate of growth of physical capital and knowledge capital reflects producers' investments in physical capital and R&D, as well as household savings decisions (which regulate the supply of investible funds to firms). In the long-run, the economy achieves steady-state growth, with excludable knowledge capital, physical capital, and produced outputs all growing at the rate of population growth. [33]

3.4. Data

3.4.1. Inter-industry flows

We apply the model to the US economy, benchmarking it to US economic activities in 1995. Most of the data on inter-industry flows derive from Department of Commerce input–output tables reported for the year 1987 in the April 1994 *Survey of Current Business*. This is also our source for value-added and for the inputs employed to produce capital good and general consumption good. We scale this information to 1995 assuming a constant real growth rate of 2.6%. [34]

The conventional energy industry includes coal, oil and natural gas extraction. The alternative energy industry includes biomass, nuclear, and hydroelectric power. The Department of Commerce data do not explicitly identify alternative energy industries. We therefore supplemented these data with more detailed information made available to us from Pacific Northwest Laboratories.

It is not possible to obtain precise data on the technology for producing R&D services. In addition, as mentioned earlier, we have no data to identify precisely the (positive) relationship between R&D services and knowledge capital. Fortunately, as discussed above, the qualitative insights emphasized in this paper do not hinge on particular functional relationships. This point is supported by the results from the sensitivity analysis in Section 4. The input–output data include the 'legal, engineering, accounting and related services' and 'other business and professional services except medical' industries. We assume that the input intensities for producing R&D services are the same as those from the combination of these two industries. In addition, we arbitrarily assume that, in each industry, the value of the

[33] Steady-state growth requires that the scale factor, $\gamma(\bar{H})$ be constant in the long-run, since production exhibits increasing returns to scale in all inputs other than non-excludable knowledge, $\bar{H}$. We therefore employ the following functional relationship:

$$\gamma(\bar{H}) = \begin{cases} \bar{H}, & \bar{H} < 2\bar{H}_0 \\ 2\bar{H}_0, & \bar{H} \geq 2\bar{H}_0 \end{cases}$$

which implies that spillover benefits eventually are exhausted, allowing a steady state. Policy changes alter the time path of $\bar{H}$ but not the ultimate value.

[34] This is the average real growth rate for the US over the period 1987–1994.

Table 2
Benchmark flows and parameter values[a]

	Input–output flows						
	EC	**EA**	**MI**	**MN**	***I***	***R***	***C***
EC	8.158	0.127	225.888	11.399	1.728	0.000	0.534
EA	0.330	0.970	3.530	11.156	0.196	0.000	10.182
MI	57.940	5.014	1904.109	1189.988	377.607	51.791	2961.235
MN	15.454	2.635	578.366	1407.016	771.366	5.517	2078.886
L	36.471	6.726	2930.853	1010.285	15.620	1.016	0.000
K	117.280	9.870	819.664	1113.548	0.000	0.000	0.000
H	13.861	1.166	96.874	131.608	0.000	0.000	0.000

GDP: 6305.7
Carbon emissions: 1.45 billion metric tons

Parameters

σ_j	1.0	(all j)
$\sigma_{\mathrm{G}j}$	1.0	(all j)
$\sigma_{\mathrm{E}j}$	0.9	(all j)
$\sigma_{\mathrm{M}j}$	1.05	(all j)
β_j	0.0	(all j)
ρ_{U}	0.5	

[a]Except where otherwise indicated, flows are in billions of 1995 dollars.

stock of knowledge capital is 20% of that of physical capital.[35] Sensitivity analysis (see Section 4) indicates that our qualitative results do not hinge on this assumption.

The benchmark inter-industry flows are shown in Table 2. Values for K and H represent factor payments (income flows), as opposed to asset values.

3.4.2. Parameters

Production elasticities are based on values employed in the larger and more disaggregated energy–environment–economy model described by Goulder (1995) and Bovenberg and Goulder (1996); Cruz and Goulder (1992) describe the sources of these elasticities in detail. Some adjustments have been made to account for the present model's greater degree of aggregation relative to the model for which the production elasticities were originally collected. The distribution parameters (α's) are identified using standard calibration techniques.[36] Adjustment cost parameters

[35] Our assumption is equivalent to the assumption that total returns to knowledge are 20% of the returns to physical capital, since the model assumes optimizing investors that require the same ex ante rate of return from investments in knowledge as from investments in physical capital.

[36] These parameters are determined from the elasticities of substitution and the requirement that observed input and output levels be consistent with first-order conditions for cost minimization. Shoven and Whalley (1992) provide a general discussion of this procedure.

are based on estimates by Summers (1981). The household's intertemporal elasticity of substitution in consumption, σ_U (equal to $1/(1-\rho_U)$), is 0.5. [37] The pure rate of time preference is 0.05. In long-run equilibrium, the after-tax return to investment in physical or knowledge capital is equal to this value.

The structure and parameterization of the model imply balanced growth in the reference (or baseline) case, as well as balanced growth in the long-run following all policy changes. The long-run growth rate of output is equal to n, the growth rate of population (and the labor force). We use a constant value of 1.25% for n. In the reference case, emissions of carbon are 1.45 billion metric tons in the benchmark year, and they grow at the same rate as the rest of the economy. This implies cumulative emissions of 116.58 billion metric tons over the period 1995–2050.

4. Simulation results

4.1. Alternative ITC scenarios

Here we examine the significance of ITC to the impacts of carbon abatement policies. To do this, we consider two scenarios: one with ITC and one without ITC (that is, with autonomous technological change). Within each scenario, we observe the impact of a carbon tax by comparing economic outcomes under the carbon tax with outcomes under a baseline, or business-as-usual, situation. By construction, the baseline economic paths are identical in the no-ITC and ITC scenarios. In the no-ITC scenario, we use a modified version of the model in which there is no R&D services industry and in which H is exogenous. In that case, we assume H grows at the same rate as population. By construction, the baseline paths are identical, even though H is endogenously determined in one scenario and exogenous in the other. Note that the two scenarios differ in terms of their treatment of *privatizable* knowledge capital (H) in production. Later on, we develop additional scenarios to examine how *spillover* knowledge $\bar{H}$ alters the impacts of carbon taxes.

4.2. Impacts of a carbon tax in the simplest setting

We now examine the impacts of a given carbon tax under alternative ITC specifications, starting with the simplest economic setting, which assumes no prior subsidies to R&D in any industry. In addition, we disregard potential knowledge spillovers: β is zero. [38] For the sake of simplicity, we consider a carbon tax that is

[37] This lies between the larger values found in cross-section analyses (e.g., Lawrance, 1991) and smaller values obtained in time series studies (e.g., Hall, 1988).

[38] Thus, $\bar{H}$ remains constant at its initial, benchmark value (equal to unity).

introduced in the benchmark year (1995) and maintained at a constant rate of US$25/ton in 1995 dollars. [39]

Fig. 2a–d displays the impacts of the carbon tax on the outputs of the energy and materials industries. The figures show, for both the ITC and no-ITC scenarios, the percentage changes from the baseline values. The impact is greatest in the conventional fuels (**EC**) industry, on which the carbon tax is imposed. The overall effect in the alternative fuels (**EA**) industry depends on three effects. Higher prices of conventional fuels lead to higher demands for alternative fuels through a substitution effect. The other two effects work in the opposite direction. Higher conventional fuels prices raises the prices of energy in general (E), which tends to reduce demands for both *EA* and *EC* through a scale effect. In addition, by 'distorting' the allocation of resources, [40] the carbon tax leads to lower real incomes and overall demand. This tax burden effect also tends to reduce demand for *EA*. In these simulations, the latter two effects dominate in the short run: in the first 10 years, *EA* output falls (relative to baseline). However, in the presence of ITC the substitution effect dominates after 10 years when ITC is present. The presence of ITC enhances the substitution effect by allowing for an expansion in the proportion of the economy's knowledge capital that resides in the **EA** industry.

For the carbon-intensive materials and non-carbon-intensive materials industries **MI** and **MN**, the tax burden effect is most important, and output falls.

The GDP losses from the tax (Fig. 3a) reflect the tax burden effect. [41] Importantly, for the given (US$25/ton) carbon tax, the losses in industry outputs and in GDP are larger in the presence of ITC than in its absence. As suggested in Section 2, ITC makes the economy more 'elastic' in a dynamic sense: it responds more fully to the tax. As a result, a given tax leads to a larger 'distortion' and gross cost. In general, the differences in costs between the ITC and no-ITC cases become larger over time. This stems from the fact that the impacts of changes in R&D effort cumulate through time: only over time can firms significantly change the stock of knowledge capital. In Fig. 3a, we also present results (dashed line) revealing the implications of the (highly unrealistic) assumption that there is no opportunity cost of R&D. This is consistent with the idea that knowledge-gener-

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[39] We consider a rising carbon tax as part of the sensitivity analysis in Section 4. Theoretical considerations and numerical optimization studies indicate that the optimal carbon tax rises at the rate of interest plus the rate of natural removal of CO_2. (See Nordhaus, 1982; Peck and Wan, 1996; Goulder and Mathai, 1998.)

[40] 'Distorting' is in quotes because an appropriately scaled carbon tax improves rather than worsens resource allocation when one accounts for the economic benefits associated with environmental improvement (or avoided damage). The lower real incomes should be seen as indicators of the carbon tax's *gross* costs—before netting out the environmental benefits.

[41] The tax burden effect is more precisely measured through equivalent variation or compensating variation measures of welfare changes, measures that are based on changes in real consumption through time. In keeping with the traditional interests of policy makers, we focus on GDP changes here.

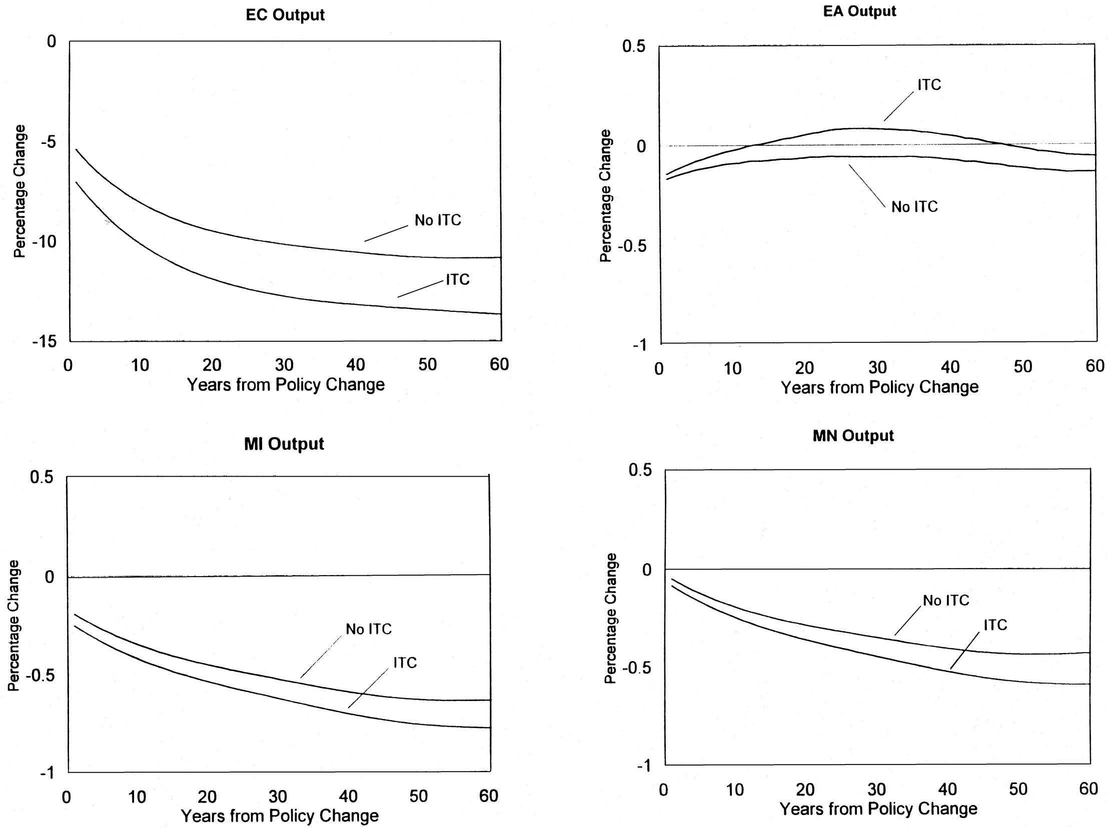

Fig. 2. Impacts of carbon tax on gross output, with and without ITC (percentage changes from baseline path).

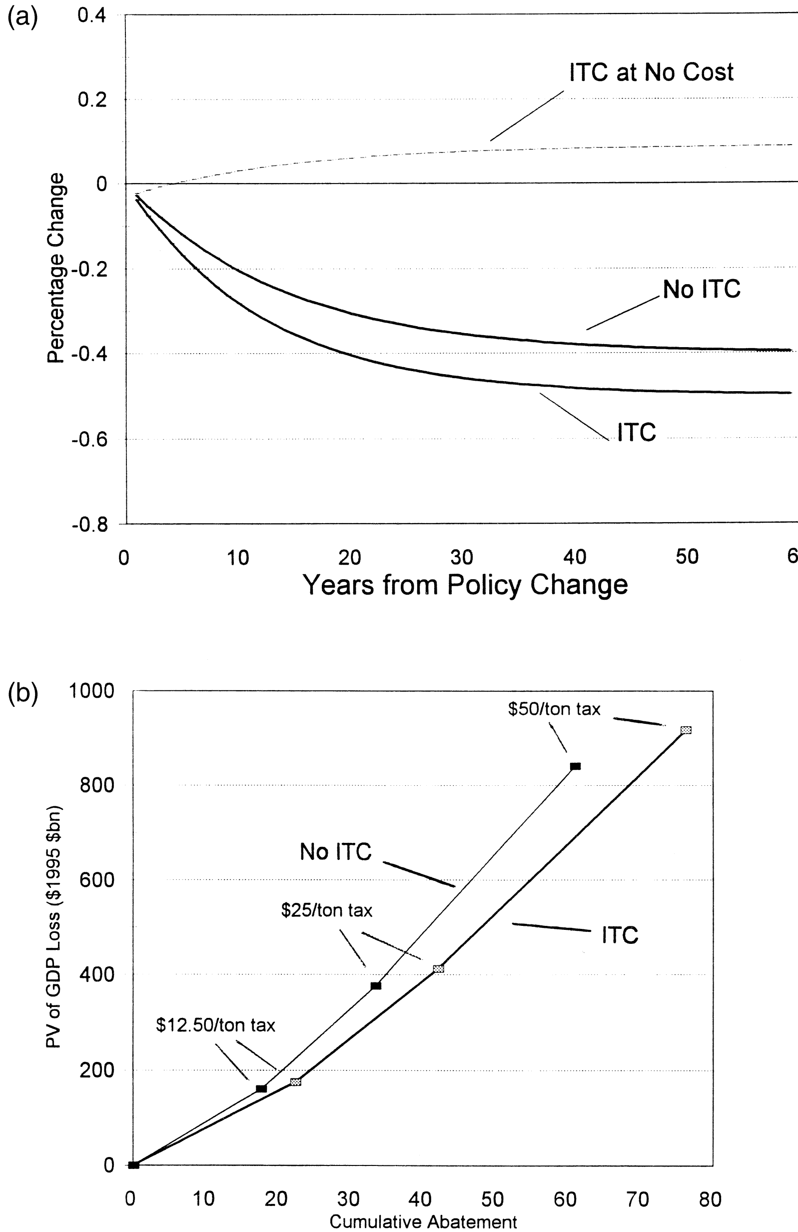

Fig. 3. (a) Impacts of carbon tax on GDP, with and without ITC. (b) GDP loss as function of abatement.

ating resources are unemployed and thus can be obtained free. In this case, we impose exogenously the changes in knowledge stocks from the normal ITC simulation, but remove the R&D industry and allow the changes in knowledge to arise free. [42] In this case, the long-run GDP impact is positive. This shows that the sign of the GDP impact of a carbon tax can differ depending on the extent of the opportunity cost of ITC.

Even *with* an accounting for opportunity costs, the presence of ITC implies larger *net benefits* from a given tax. One way to observe this is to compare the costs of achieving given reductions in emissions in the presence and absence of ITC. [43] Fig. 3b shows the relationship between emissions reductions and the present value of the GDP losses. To demonstrate the principle simply, we time-aggregate the emissions reductions by taking the present value of the reductions. [44] On each curve in the figure, the points marked by shaded rectangles show results under carbon taxes of US$12.50/ton (lower left), US$25/ton (middle), and US$50/ton (top right). The curve for the ITC case lies below that for the no-ITC case: the GDP cost associated with achieving *any given level of abatement* is lower in the presence of ITC. This result also squares with the heuristic presentation of Section 2, and reflects the economy's greater 'elasticity' of abatement with respect to the cost of carbon-based fuels. For example, achieving cumulative abatement of 40 billion metric tons involves a GDP sacrifice of about US$375 billion in the presence of ITC, as compared with about US$500 billion in its absence. [45]

[42] We cannot incorporate endogenous knowledge accumulation in this case, because the zero cost of R&D would imply infinite investment in knowledge in our model.

[43] To the extent that standardizing the amount of emissions reduction keeps gross benefits constant, policies that achieve given reductions at lower gross cost also enjoy larger net benefits.

[44] If marginal damages from emissions are constant, then the present value of emissions reductions is proportional to the present value of the environmental benefits. In taking present values, we use the equilibrium interest rates from the simulations.

[45] These results might appear to contradict very recent results by Nordhaus (1997) indicating that the presence of ITC has an imperceptible impact on the optimal profile of abatement and the optimal carbon tax. However, as shown by Goulder and Mathai (1998), there is no inconsistency here. They show that if (1) the marginal abatement cost function is very steep in the relevant range, and (2) the marginal damages from increments to CO_2 concentrations are flat in the relevant range (i.e., the range of concentrations that result in the baseline or under the policies in question), then the optimal profiles for carbon taxes and for abatement levels are insensitive to the presence or absence of ITC. These conditions seem to apply to Nordhaus's model. In contrast, the present model does not meet the first condition above: as indicated by Fig. 3b: the marginal abatement cost functions (where cost is measured in terms of GDP) are not extremely steep at the level of abatement under consideration. As a result, a given carbon tax leads to different levels of abatement in the presence and absence of ITC. The figure does not include a damage function, and thus it does not provide enough information to determine *optimal* tax rates or abatement levels. But if one were to include damage functions in the figure, the sensitivity of optimal abatement and optimal taxes to ITC could be explained in terms of the two conditions referred to here.

Fig. 4 shows the impacts of the US$25/ton carbon tax on R&D expenditure by the different industries and in the aggregate. The impacts are measured as percentage changes from the baseline levels. The carbon tax prompts a significant increase in R&D by the alternative energy industry, and a smaller increase (in percentage terms) by the materials industries. At the same time, the tax induces significant reductions in R&D expenditure (relative to baseline) by the conventional fuels industry, upon which the tax is imposed. Indeed, R&D expenditure drops to zero in this industry in the first 3 years following the imposition of the US$25/ton tax. The aggregate level of R&D actually falls (relative to baseline) as a result of the tax. Increased technological progress in some industries usually is accompanied by reduced rates of technological progress in others. Although a carbon tax raises the profitability of given R&D investments in alternative (low-carbon or carbon-free) energy, it reduces the profitability of such investments in conventional energy by raising the relative price of carbon-based energy and thereby lowering expected future demands. In addition, to the extent that a carbon tax lowers overall incomes (ignoring future environmental benefits), it implies lower demands for products of other industries. This also tends to reduce incentives for R&D. The reduced investments in R&D are reflected in lower levels of future GDP. Models that fail to recognize these effects are likely to understate the GDP costs from a carbon tax.

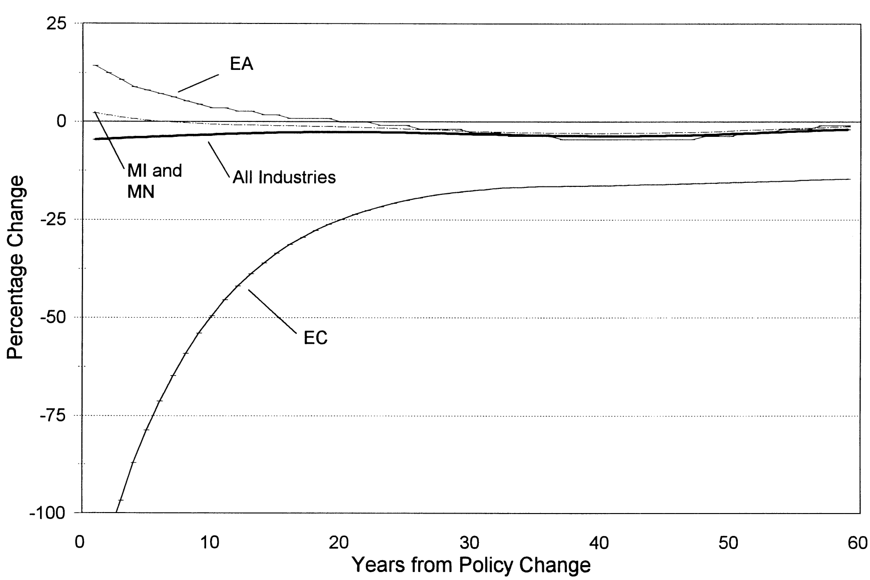

Fig. 4. Impacts on R&D expenditure (percentage changes from baseline path).

4.3. Implications of inefficiencies in R&D markets

To this point, we have ignored the possibility that R&D markets are inefficient. Such inefficiencies can influence the impacts of carbon taxes in the presence of ITC. As discussed in Section 2, efficiency in the R&D markets requires that subsidies to R&D be aligned with the magnitudes of knowledge spillovers (external benefits) from R&D: the subsidy rate should match the value of the spillover benefit.

Mismatches between prior subsidies and spillovers affect the costs of a carbon tax in the presence of ITC. In Fig. 5a, we consider cases where there are prior subsidies to R&D, despite the (assumed) absence of spillovers. Specifically, we compare cases where (a) the **EC** industry enjoys a 10% ad valorem subsidy ($\nu_{\mathrm{EC}} = 0.1$), (b) no industry enjoys a subsidy, and (c) the **EA** industry enjoys a 10% subsidy ($\nu_{\mathrm{EA}} = 0.1$). The GDP costs of a US$25/ton carbon tax are lowest in case (a) and highest in case (c), although the differences across the cases are not very large. In the absence of spillovers, a subsidy to R&D in a given industry means that in the baseline R&D is overallocated to the subsidized industry in the sense that the marginal social value of R&D is lower in that sector than in other sectors. The carbon tax causes a reallocation of R&D away from *EC* and toward *EA* and other sectors. In case (a), the opportunity cost of moving R&D away from *EC* is lower, because R&D is relatively unproductive in that sector as a result of the prior subsidy. In case (c), the opportunity cost is higher, because the prior subsidy to **EA** causes R&D in the **EC** industry to be relatively productive.

In Fig. 5b, we consider cases where there are knowledge spillovers but no subsidies to R&D. Here we compare cases where (a) there are knowledge spillovers in **EC** only, (b) knowledge spillovers in **EC** and **EA**, and (c) knowledge spillovers in **EA** only. We employ a value of 0.2 for β in the spillover cases. The GDP costs (relative to baseline) [46] are highest when spillovers apply to **EC** alone, and smallest when they apply to **EA** alone. The reasoning is the same as that for the subsidy cases. If spillovers are exceptionally high in the **EC** industry, prior to imposing the carbon tax the marginal social value of R&D is higher in that industry than in others. Thus, the opportunity cost of reallocating R&D toward other industries is especially high in this case.

4.4. ITC and the case for an R&D subsidy

In Fig. 6, we present results bearing on the issue of whether the potential for ITC justifies a subsidy to R&D in alternative fuels. Here we consider two

[46] In contrast with previous cases, in the spillover cases, the baseline paths are not the same under different spillover assumptions.

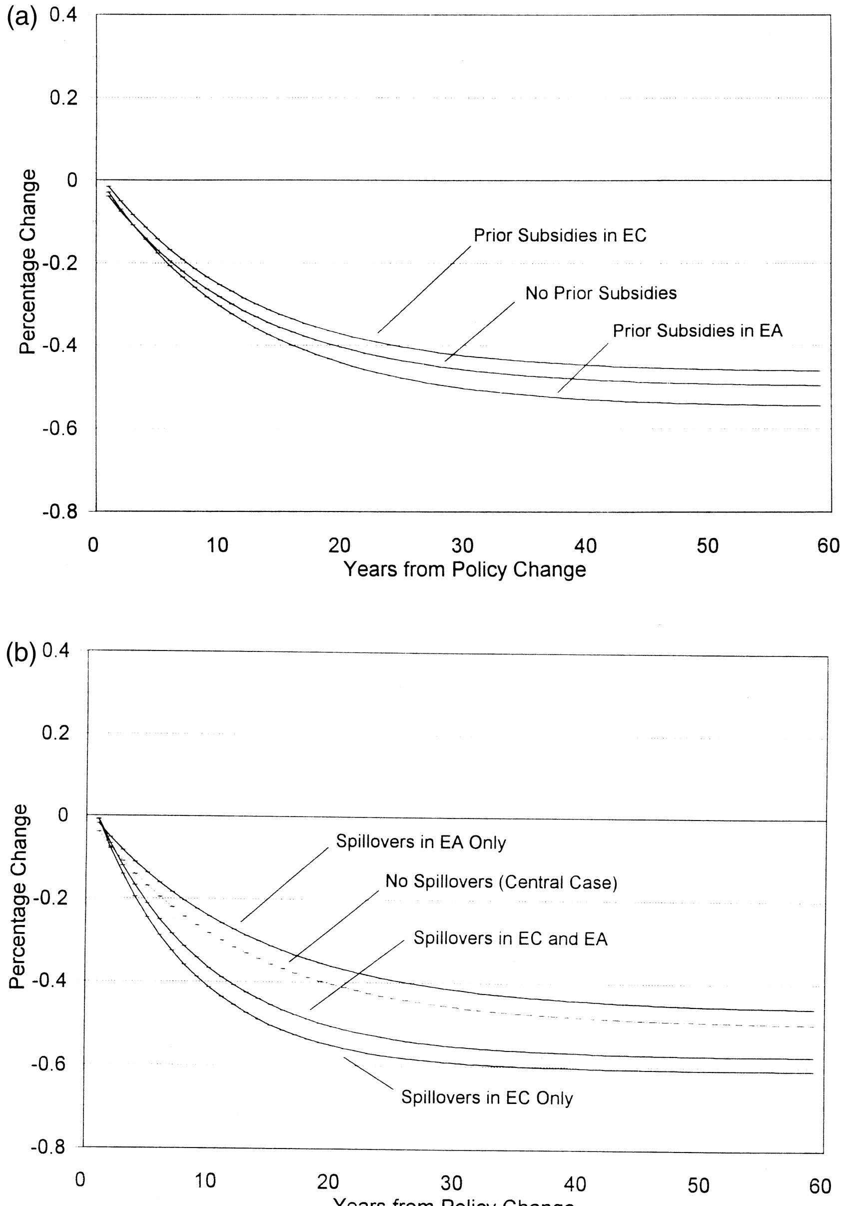

Fig. 5. (a) GDP impacts of US$25/ton carbon tax under alternative assumptions for pre-existing subsidies. (b) GDP impacts of US$25/ton carbon tax under alternative spillover assumptions.

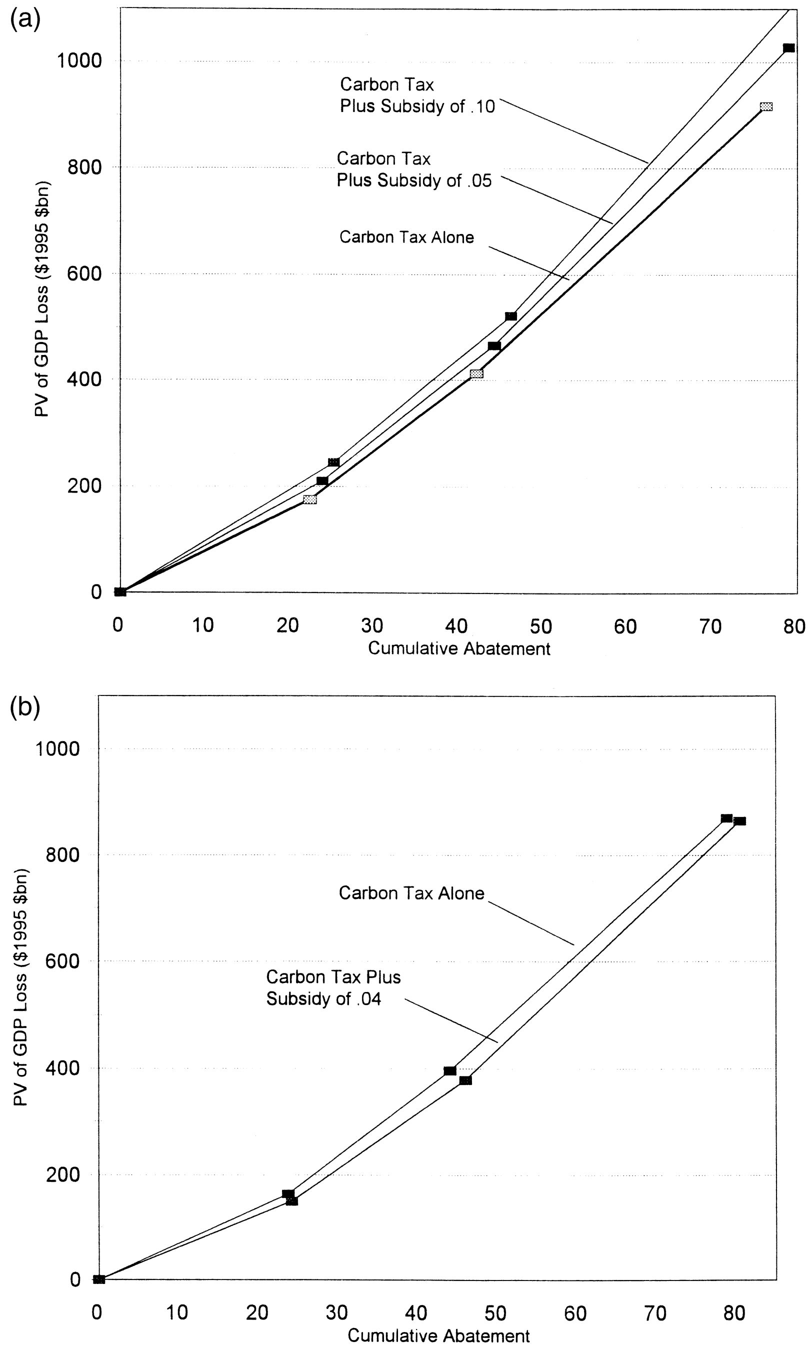

Fig. 6. (a) Effects of R&D subsidies, no spillovers. (b) Effects of R&D subsidies, spillovers in EA.

scenarios. Fig. 6a gives results from a scenario in which it is assumed that there are no knowledge spillovers in any industry. Fig. 6b offers results from a scenario in which the **EA** industry (alone) enjoys knowledge spillovers (stemming from a value of 0.2 for β). If there are no knowledge spillovers (Fig. 6a), the costs of achieving given reductions in emissions are lowest with no R&D subsidy: R&D subsidies in fact raise the costs of achieving targeted reductions. On the other hand, if there are knowledge spillovers (Fig. 6b), an R&D subsidy can reduce the costs of achieving a given emissions target. In this latter case, only modest subsidies (below 0.6) reduce overall policy costs. Subsidies above this value (when β in **EA** equals 0.2) significantly exceed the rate that can be justified in light of the spillovers, and raise policy costs.

These results indicate that ITC per se is not a rationale for subsidies to R&D in alternative fuels. Knowledge spillovers—the *external* benefits from R&D—provide such a rationale. [47]

4.5. Sensitivity analysis

Table 3 shows results from further sensitivity analysis. We consider the GDP costs of a given carbon tax (US$25/ton) and of attaining a given (30%) reduction, relative to the baseline, in the present value of cumulative emissions. The GDP cost is the present value of the reduction in GDP over the interval 1995–2070.

Recalibrating the model to double the initial values of knowledge stocks (H_0) in each industry gives more potency to ITC. The doubling means that H_0 has a larger share parameter in the production function; hence, knowledge has a more important role in production. Relative to the central case, doubling H_0 raises the GDP losses from given carbon taxes but lowers the GDP costs of achieving the target reductions. Lowering the H_0's has the opposite effect. Lowering (raising) the costs of producing R&D services also strengthens (weakens) importance of ITC. Raising the value of ϵ has a similar effect to that of lowering the costs of R&D services—effectively, a higher ϵ means that the cost of achieving effective R&D services (that is, increase in H) falls. Higher values for σ_X make it easier to substitute H for other productive factors. This flexibility heightens the significance of ITC, and implies higher GDP costs of a given tax and lower costs of achieving given targets. Higher values for σ_E do not have much impact on the differences between the costs in the ITC and no-ITC cases. To a similar degree in both cases, they imply higher GDP costs of a given tax and lower costs of achieving given targets.

In sum, whenever parameters are changed to make stocks of knowledge more important as a productive input, cheaper to acquire, or more easily substitutable

[47] These issues are explored further in Schneider and Goulder (1997). It may be noted that the government can deal with spillovers through other instruments, such as direct grants supporting R&D.

Table 3
Further sensitivity analysis

Case	Percentage reduction in PV of GDP			
	From US$25/ ton carbon tax		From 30% reduction in cumulative emissions	
	ITC	No ITC	ITC	No ITC
Central case parameter values	0.253	0.231	0.154	0.198
H_0 doubled	0.280	0.234	0.122	0.199
H_0 halved	0.238	0.230	0.184	0.198
R industry production costs doubled	0.241	0.232	0.148	0.200
R industry production costs halved	0.276	0.229	0.170	0.198
ϵ doubled	0.260	0.231	0.157	0.198
ϵ halved	0.249	0.231	0.150	0.198
σ_X doubled	0.276	0.231	0.150	0.198
σ_X halved	0.240	0.231	0.157	0.198
σ_E doubled	0.311	0.281	0.124	0.157
σ_E halved	0.209	0.191	0.180	0.234

Figures are the percentage changes in the present value of GDP over the 75-year interval from 1995 to 2070, evaluated using a discount rate of 5% (the benchmark and steady-state value). The emission reduction is a 30% reduction in the present value of cumulative emissions over this interval. Central case values for H_0 are in Table 1. Central case values for ϵ and ρ_X are unity in each industry. In some cases, changes in ITC-related parameters yield different baseline paths; as a result, the percentage changes for the no-ITC cases can be influenced by these parameter changes.

with other factors, GDP costs of a given carbon tax rise and the costs of reaching given abatement targets fall.

5. Conclusions

In this paper, we have developed a simple analytically tractable model, along with a more elaborate numerical model, to examine the implications of ITC for CO_2 abatement policy. The numerical model is distinct from other disaggregated general equilibrium models in capturing explicitly the connections between climate policies, incentives to engage in R&D, the supply of knowledge-generating resources, and the rate of technological change.

Our models emphasize the importance of taking into account the cost of inducing technological change. Unless there is a free (unemployed) pool of knowledge-generating resources, the expansion of knowledge-generation in one in sector comes at a cost. We show that the GDP costs of carbon taxes are dramatically different depending on whether one takes account of the costs of attaining knowledge-generating resources.

Similarly, our numerical model indicates that the impacts of a carbon tax on R&D can differ significantly across industries. Although a carbon tax stimulates R&D in alternative energy industries, it tends to discourage R&D by non-energy industries and by conventional, carbon-based energy industries. The reduction in R&D in these industries implies slower growth of output in these industries, which is reflected in future levels of GDP. Models that ignore these effects are likely to understate the GDP costs from a carbon tax.

Nevertheless, ITC generally makes climate policies more attractive. The *net benefits* from a given carbon tax are higher in the presence of ITC, even though the *gross costs* of the tax are raised as well. Evaluating carbon taxes by attending only to the gross costs (e.g., the GDP costs before netting out the economic benefits from avoided climate damages), therefore, can lead to erroneous policy conclusions.

In most of the cases that we examine, the presence of ITC does not introduce the possibility of zero-cost carbon abatement. Serious pre-existing inefficiencies in R&D markets can imply low gross costs of abatement, but the zero-cost outcome requires the social opportunity cost of R&D to be zero or negative. In our numerical simulations, we were unable to produce the zero-cost outcome under plausible values for parameters. The inability of ITC to yield zero costs of a carbon tax in no way vitiates the case for a carbon tax. Net benefits from such a policy still may be positive. Indeed, in our numerical model and in many other carbon tax studies, the marginal costs of the carbon tax are initially zero, so that an appropriately scaled carbon tax will produce net benefits as long as the environmental effects are beneficial overall.

Although our focus in this paper is R&D-based technological change, the phenomenon of divergent impacts on technological change can apply to *learning-by-doing-based* technological change as well. A carbon tax may encourage learning-by-doing-based technological change related to the production of alternative fuels. At the same time, however, the tax leads to a reduction in output (and, therefore, cumulative output or ‘experience’) in other industries. This means that, as a consequence of the carbon tax, in these other industries, the rate of technological progress from learning-by-doing is lower than otherwise would be the case. Hence, climate policies that promote learning-by-doing in some industries also reduce the rate of learning-by-doing in other industries. Thus, models that include learning-by-doing selectively could bias the assessments of policy costs. However, it should be recognized that the industries most harmed by a carbon tax—namely, the conventional energy industries—tend to be mature industries where learning-by-doing effects could be fairly small.

Some limitations of the present study deserve attention. First, this paper’s results are largely qualitative. Our ability to generate more precise estimates is fundamentally limited by the absence of empirical estimates on the relationships between R&D expenditure and technological change. In addition, the present study only focuses on R&D by the private sector. Assessing the benefits and costs of public R&D efforts introduces economic issues that are beyond the scope of this paper. Despite these limitations, these models offer some guidelines that can be useful for integrated assessment modeling and policy evaluation.

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Appendix A. Proofs of propositions in Section 2

Note: propositions 1–3 all depend on the assumption that the social cost of R&D equals the private cost (i.e., that $p_R = \hat{p}_R$). Proposition 4 deals with the case in which this assumption does not hold.

Proposition 1. *ITC lowers the gross social cost of achieving a given level of emissions.*

Let A_1^*, A_2^*, R_1^* denote the (private-cost-minimizing) optimum choices of abatement and R&D investment when no ITC is possible, and let A_1^C, A_2^C, R_1^C denote the (private-cost-minimizing) constrained optimum when ITC is possible and emissions are constrained to equal the same level as in the no-ITC case (i.e., $A_1 + A_2 = \bar{A} = A_1^* + A_2^*$).

Since A_1^*, A_2^*, R_1^* meets the constraint, $\mathrm{PC}(A_1^*, A_2^*, R_1^*) \geq \mathrm{PC}(A_1^C, A_2^C, R_1^C)$ by definition of a constrained optimum. Because firms take τ as given and emissions are constrained to the same level in both cases, this implies $c(A_1^*, H_1^*) + c(A_2^*, H_2^*) + p_R R_1^* \geq c(A_1^C, H_1^C) + c(A_2^C, H_2^C) + p_R R_1^C$.

Assuming that $p_R = \hat{p}_R$, this is equivalent to $\mathrm{GSC}(A_1^*, A_2^*, R_1^*) \geq (A_1^C, A_2^C, R_1^C)$.

Proposition 2. *ITC has an ambiguous effect on the gross social cost of a given carbon tax, but is likely to raise gross social costs.*

Here we use the constant a as a measure of the feasibility of ITC. If $a = 0$ then ITC is not feasible, and as a rises, the effect of ITC grows. Taking a total derivative of the gross social cost and assuming that $\hat{p}_R = p_R$ yields

$$\frac{\mathrm{dGSC}}{\mathrm{d}a} = \frac{\partial c}{\partial A_2}\frac{\mathrm{d}A_2}{\mathrm{d}H_2}\left(\zeta(R_1) + a\frac{\partial\zeta}{\partial R_1}\frac{\mathrm{d}R_1}{\mathrm{d}a}\right) + \frac{\partial c}{\partial H_2}\left(\zeta(R_1) + a\frac{\partial\zeta}{\partial R_1}\frac{\mathrm{d}R_1}{\mathrm{d}a}\right) + p_R\frac{\mathrm{d}R_1}{\mathrm{d}a}$$

Differentiating the private cost function (PC) with respect to the choice variables A_1, A_2, and R_1, setting each derivative equal to zero and solving yields the following first-order conditions which describe the private-cost-minimizing solution:

$$\frac{\partial c}{\partial A_1} = \tau;\ \frac{\partial c}{\partial A_2} = \tau;\ \frac{\partial c}{\partial H_2}\frac{\partial\zeta}{\partial R_1} = -p_R$$

Substituting in the first-order conditions for the firm's choices of A_2 and H_2 into the expression for the total derivative above and canceling terms gives

$$\frac{\mathrm{dGSC}}{\mathrm{d}a} = \tau\frac{\mathrm{d}A_2}{\mathrm{d}H_2}\left(\zeta(R_1) + a\frac{\partial\zeta}{\partial R_1}\frac{\mathrm{d}R_1}{\mathrm{d}a}\right) + \frac{\partial c}{\partial H_2}\zeta(R_1)$$

Assuming that $[(\mathrm{d}R_1)/(\mathrm{d}a)] > 0$ (i.e., that the more feasible ITC is, the more research the firm will conduct) it follows that the first term in this expression is positive. The second term will either be zero or negative. If the second term is negative, then the sign of the derivative is ambiguous. However, assuming that $\zeta(0) = 0$ (i.e., that without any R&D, the firm will not gain any knowledge) the second term will be zero when a is sufficiently low to ensure that R_1 is zero. Thus, small amounts of ITC will necessarily raise gross social cost. For larger changes, ITC may reduce gross social cost, but only if abatement costs are very sensitive to the stock of knowledge (i.e., if the absolute value of $(\partial c)/(\partial H_2)$ is large) or if the optimal amount of abatement is very insensitive to the stock of knowledge (i.e., if $(\mathrm{d}A_2)/(\mathrm{d}H_2)$ is small).

Proposition 3. *ITC raises net social benefits of a given carbon tax.*

Let A_1^*, A_2^*, R_1^* denote the optimum choices of abatement and R&D investment when no ITC is possible, and A_1^I, A_2^I, R_1^I denote the optimum when ITC is possible.

By the definition of an optimum, $\mathrm{PC}(A_1^*, A_2^*, R_1^*) \geq \mathrm{PC}(A_1^I, A_2^I, R_1^I)$.

Adding the expression for private cost to the expression for net social benefit given earlier, canceling terms and rearranging gives

$$\mathrm{NSB} = \tau\bar{E} - \mathrm{PC} + (D - \tau)(A_1 + A_2) + R_1(p_R - \hat{p}_R)$$

if $\tau = D$ and $p_R = \hat{p}_R$ then the last two terms each equal zero, so net social benefits equal a constant minus private costs. Thus, $\mathrm{PC}(A_1^*, A_2^*, R_1^*) \geq \mathrm{PC}(A_1^I, A_2^I, R_1^I)$ implies $\mathrm{NSB}(A_1^I, A_2^I, R_1^I) \geq \mathrm{NSB}(A_1^*, A_2^*, R_1^*)$.

Proposition 4. *Pre-existing distortions in the R&D market influence the gross social costs of an abatement policy.*

If $p_R \neq \hat{p}_R$ then the total derivative used in the proof of proposition 2 becomes

$$\frac{\mathrm{dGSC}}{\mathrm{d}a} = \frac{\partial c}{\partial A_2}\frac{\mathrm{d}A_2}{\mathrm{d}H_2}\left(\zeta(R_1) + a\frac{\partial \zeta}{\partial R_1}\frac{\mathrm{d}R_1}{\mathrm{d}a}\right) + \frac{\partial c}{\partial H_2}\left(\zeta(R_1) + a\frac{\partial \zeta}{\partial R_1}\frac{\mathrm{d}R_1}{\mathrm{d}a}\right) + \hat{p}_R\frac{\mathrm{d}R_1}{\mathrm{d}a}$$

In this case, substituting in the first-order conditions and collecting terms gives

$$\frac{\mathrm{dGSC}}{\mathrm{d}a} = \tau\frac{\mathrm{d}A_2}{\mathrm{d}H_2}\left(\zeta(R_1) + a\frac{\partial \zeta}{\partial R_1}\frac{\mathrm{d}R_1}{\mathrm{d}a}\right) + \frac{\partial c}{\partial H_2}\zeta(R_1) + (\hat{p}_R - p_R)\frac{\mathrm{d}R_1}{\mathrm{d}a}$$

which is simply the expression from the proof of proposition 2 plus an extra term.

Thus, if the social cost is greater than the private cost of R&D then the gross social costs of the carbon tax will be increased by the distortion in the R&D market. Conversely, if the social cost is less, then the gross social costs will be decreased by the distortion.

Rearranging the last equation demonstrates that if the difference between the social and private costs of R&D is sufficiently large that

$$(p_R - \hat{p}_R)\frac{\mathrm{d}R_1}{\mathrm{d}a} \geq \tau\frac{\mathrm{d}A_2}{\mathrm{d}H_2}\left(\zeta(R_1) + a\frac{\partial \zeta}{\partial R_1}\frac{\mathrm{d}R_1}{\mathrm{d}a}\right) + \frac{\partial c}{\partial H_2}\zeta(R_1)$$

then the gross social costs of a carbon tax are necessarily lower in the presence of ITC than in its absence.

However, unless the social cost of R&D is negative, the carbon tax will still have a positive gross social cost even in the presence of ITC. Since gross social cost is the sum of abatement costs and R&D costs, gross social cost can fall to zero only if the social cost of R&D is sufficiently negative to offset the costs of abatement.

Appendix B. Structure of the numerical model

Note: Unless otherwise indicated, the industry subscript j ranges over industries **EA**, **EC**, **MI**, **MN**, **I**, **R**, and **C**.

B.1. Parameters

α_{ij}	distribution parameter for input i used by representative firm in industry j
α_N	ratio of labor force to population
β	parameter influencing growth of spillover knowledge
δ_j	rate of economic depreciation of physical capital by representative firm in industry j
η_j	parameter of adjustment cost function for industry j

λ_{jt}	shadow value of physical capital to representative firm in industry j at time t
μ_{jt}	shadow value of knowledge capital to representative firm in industry j at time t
ξ_t	shadow value of household wealth at time t
ρ_j	substitution parameter for production function of representative firm in industry j
ρ_{Ej}	substitution parameter for energy aggregation function of representative firm in industry j
ρ_{Mj}	substitution parameter for materials aggregation function of representative firm in industry j
ρ_U	intertemporal elasticity of substitution in consumption
σ_j	elasticity of substitution between H and G in production by representative firm in industry j
σ_{Gj}	elasticity of substitution between inputs K, L, E, and M in input composite G of representative firm in industry j
σ_{Ej}	elasticity of substitution between EC and EA in energy aggregation function of representative firm in industry j
σ_{Mj}	elasticity of substitution between MI and MN in materials aggregation function of representative firm in industry j
τ_j	per-unit tax rate applied to output of industry j
υ_j	ad valorem subsidy to R&D expenditure by industry j
ω	pure rate of time preference

B.2. Endogenous variables

a_{ijt}	input intensity for i in industry j at time t
C_t	per-capita consumption at time t
E_{jt}	use of composite energy by representative firm in industry j at time t
EA_{jt}	use of alternative energy by representative firm in industry j at time t
EA_{AD_t}	aggregate demand for alternative energy at time t
EC_{jt}	use of conventional energy by representative firm in industry j at time t
EC_{AD_t}	aggregate demand for conventional energy at time t
H_{jt}	stock of knowledge for representative firm in industry j at time t
$\overline{H}_{jt}$	spillover knowledge applied to industry j at time t
I_{jt}	investment in physical capital by industry j at time t
I_{AD_t}	aggregate investment demand at time t
K_{jt}	stock of physical capital used by representative firm in industry j at time t
L_{jt}	labor employed by industry j at time t
L_{AD_t}	aggregate labor demand at time t
L_{AS_t}	aggregate labor supply at time t

M_{jt} use of composite materials by representative firm in industry j at time t
MI_{jt} use of energy-intensive materials by representative firm in industry j at time t
MI_{AD_t} aggregate demand for energy-intensive materials at time t
MN_{jt} use of non-energy-intensive materials by representative firm in industry j at time t
MN_{AD_t} aggregate demand for non-energy-intensive materials at time t
N_t population at time t
p_{Ct} price of consumption good at time t
p_{ijt} price of input i to representative firm j at time t
p_{It} price of new capital goods at time t
p_{Lt} price of labor at time t
p_{Rt} price of R&D services at time t
R_{jt} R&D services employed by representative firm j at time t
R_{AD_t} aggregate demand for R&D services at time t
S_t value of aggregate household saving at time t
U_t intertemporal utility of household, evaluated at time t
V_{jt} value of firm j at time t
W_{Ft} financial wealth of household at time t
X_{jt} output gross of adjustment costs of firm j at time t
Y_t aggregate income at time t
Y_{Lt} aggregate labor income at time t
Y_{Gt} aggregate government transfer income at time t
γ_{jt} scale factor for production function of representative firm j at time t
π_{jt} gross profit of representative firm j at time t
Φ_{jt} per-unit adjustment costs of representative firm j at time t

B.3. Equations

B.3.1. Production technologies and the firm's maximization problem

In the energy and materials industries (**EC**, **EA**, **MI**, and **MN**), output gross of adjustment costs is produced according to:

$$X = \gamma(\overline{H})(\alpha_H H^{\rho_x} + \alpha_G G^{\rho_x})^{1/\rho_x} \quad \text{(B1)}$$

where:

$$G = (\alpha_K K^{\rho_G} + \alpha_L L^{\rho_G} + \alpha_E E^{\rho_G} + \alpha_M M^{\rho_G})^{1/\rho_G} \quad \text{(B2)}$$

$$E_{jt} = \left(\alpha_{ECj} EC_{jt}^{\rho_{Ej}} + \alpha_{EAj} EA_{jt}^{\rho_{Ej}}\right)^{\frac{1}{\rho_{Ej}}} \quad \text{(B3)}$$

$$M_{jt} = \left(\alpha_{MIj} MI_{jt}^{\rho_{Mj}} + \alpha_{MNj} MN_{jt}^{\rho_{Mj}}\right)^{\frac{1}{\rho_{Mj}}} \quad \text{(B4)}$$

In the capital goods, R&D services, and consumer goods industries (**I**, **R**, and **C**), the production technology is:

$$X_j = \gamma_j\left(\alpha_{\mathrm{L}j} L_j^{\rho_{\mathrm{X}j}} + \alpha_{\mathrm{E}j} E_j^{\rho_{\mathrm{X}j}} + \alpha_{\mathrm{M}j} M_j^{\rho_{\mathrm{X}j}}\right)^{\frac{1}{\rho_{\mathrm{X}j}}} \tag{B5}$$

where E_{jt} and M_{jt} are defined by Eqs. (B3) and (B4) above.

Physical capital and knowledge capital accumulate according to:

$$K_{j,t+1} = (1-\delta_j) K_{jt} + I_{jt} \tag{B6}$$

$$H_{j,t+1} = H_{jt} + \epsilon R_{jt} \tag{B7}$$

In the **EC**, **EA**, **MI**, and **MN** industries, the maximization problem for the firm is:

$$\max V_t = \sum_{s=t}^{\infty}\Big[(p_{js}-\tau_j)\big(X_{js}(\cdot) - \phi_{js}(\cdot) I_{js}\big) - p_{\mathrm{E}js} E_{js} - p_{\mathrm{M}js} M_{js}$$
$$- p_{\mathrm{L}s} L_{js} - p_{\mathrm{I}s} I_s - (1-v_{js}) p_{\mathrm{R}s} R_s\Big] d(t,s) \tag{B8}$$

where the discounting operator, $d(t,s)$, is defined by

$$d(t,s) = \begin{cases} 1, & s = t \\ \prod_{v=t}^{s-1} (1+r_s)^{-1}, & s > t \end{cases}$$

and r_s denotes the market rate of return from period s to period $s+1$.

In the **I**, **R**, and **C** industries, the problem is to maximize current profits in each period:

$$\max \Pi_t = (p_{jt}-\tau_j) X_{jt} - p_{\mathrm{E}jt} E_{jt} - p_{\mathrm{M}jt} M_{jt} \tag{B9}$$

The prices $p_{\mathrm{E}js}$, $p_{\mathrm{M}js}$ in Eqs. (B8) and (B9) are the minimal unit costs of obtaining the energy and materials composites E and M. From the dual cost functions to Eqs. (B3) and (B4):

$$p_{\mathrm{E}js} = \left[\alpha_{\mathrm{EC}j}^{-1/(1-\rho_{\mathrm{E}j})} p_{\mathrm{EC}}^{-\rho_{\mathrm{E}j}/(1-\rho_{\mathrm{E}j})} + \alpha_{\mathrm{EA}j}^{-1/(1-\rho_{\mathrm{E}j})} p_{\mathrm{EA}}^{-\rho_{\mathrm{E}j}/(1-\rho_{\mathrm{E}j})}\right]^{(1-\rho_{\mathrm{E}j})/\rho_{\mathrm{E}j}} \tag{B10}$$

$$p_{\mathrm{M}js} = \left[\alpha_{\mathrm{MI}j}^{-1/(1-\rho_{\mathrm{M}j})} p_{\mathrm{MI}}^{-\rho_{\mathrm{M}j}/(1-\rho_{\mathrm{M}j})}\right.$$
$$\left. + \alpha_{\mathrm{MN}j}^{-1/(1-\rho_{\mathrm{M}j})} p_{\mathrm{MN}}^{-\rho_{\mathrm{M}j}/(1-\rho_{\mathrm{M}j})}\right]^{(1-\rho_{\mathrm{M}j})/\rho_{\mathrm{M}j}} \tag{B11}$$

The adjustment cost function in Eq. (B8) is:

$$\Phi_{jt} = \frac{1}{2}\eta\left(I_{jt}/K_{jt} - \delta_j\right)^2 / \left(I_{jt}/K_{jt}\right) \tag{B12}$$

In the energy and materials industries, firms maximize V subject to the production technology (Eqs. (B1), (B2), (B3) and (B4)), the capital accumulation conditions

(Eqs. (B5) and (B6)), the requirement that E and M be obtained at minimum cost (Eqs. (B10) and (B11)), and the adjustment cost function (Eq. (B12)). The constrained optimization problem yields the following Lagrangian expression: [48]

$$\mathscr{L} = \sum_{s=t}^{\infty} \Big[(p_{js} - \tau_j)\big(X_{js}(\cdot) - \Phi_{js}(\cdot) I_{js} \big) - p_{\mathrm{E}js} E_{js} - p_{\mathrm{M}js} M_{js} - p_{\mathrm{L}s} L_{js} - p_{\mathrm{I}s} I_{js} - (1 - v_{js}) p_{\mathrm{R}s} R_{js} \Big] d(t,s) - \sum_{s=t}^{\infty} \lambda_{js} \big[K_{j,s+1} - (1-\delta) K_{js} - I_{js} \big] d(t,s) - \sum_{s=t}^{\infty} \mu_{js} \big[H_{j,s+1} - H_{js} - \epsilon R_{js} \big] d(t,s) \quad \text{(B13)}$$

In the other industries firms maximize π subject to the production technology and minimum cost conditions.

B.3.2. Optimal input and investment demands

B.3.2.1. Variable inputs. Differentiating Eq. (B13) or Eq. (B9) with respect to the variable inputs x_{js} $(x = E,\ M,\ L)$ yields the usual marginal productivity condition, $(p_j - \tau_j)\partial f_j / \partial x_j = p_{xj}$. Evaluating this condition with the CES production functions in Eqs. (B1) and (B2) yields the following optimal input intensities:

$$a_{xj} \equiv \frac{x_j}{G_j} = \left[\frac{p_{\mathrm{G}j} \alpha_{xj}}{p_x} \right]^{1/(1-\rho_{\mathrm{G}j})} \quad \text{(B14)}$$

$$a_{\mathrm{G}j} \equiv \frac{G_j}{X_j} = \left[\gamma_j^{\rho_{\mathrm{X}j}} \frac{(p_j - \tau_j)\alpha_{\mathrm{G}j}}{p_{\mathrm{G}j}} \right]^{1/(1-\rho_{\mathrm{X}j})} \quad \text{(B15)}$$

for $x = E,\ M,\ L.$

Optimal choices of EC and EA, or of MI and MN, are such as to minimize the cost of obtaining E or M. The input intensities satisfying the minimum cost condition are:

$$a_{\mathrm{EC}\,j} \equiv EC_j / E_j = \left(\frac{\alpha_{ECj}\, p_{EC}}{p_{Ej}} \right)^{1/(1-\rho_{\mathrm{E}j})} \quad \text{(B16)}$$

$$a_{\mathrm{EA}\,j} \equiv EA_j / E_j = \left(\frac{\alpha_{EAj}\, p_{EA}}{p_{Ej}} \right)^{1/(1-\rho_{\mathrm{E}j})} \quad \text{(B17)}$$

Analogous expressions apply for a_{MIj} and a_{MNj}.

[48] For ease of exposition, in writing the Lagrangean, we simply represent output by X rather than use (B2–B5) to express it as a function of inputs.

B.3.2.2. Optimal investment and R&D expenditure. Differentiating the Lagrangian expression (B13) with respect to I_s, R_s, K_{s+1} and H_{s+1} yields the first-order conditions:

$$(p_{js}-\tau_j)\Phi_{js}+\Phi'_{js}I_{js}K_{js}^{-1}+p_{\mathrm{I}s}=\lambda_{js} \tag{B18}$$

$$(1-\upsilon_j)p_{\mathrm{RS}}=\mu_{js} \tag{B19}$$

$$\Big[(p_{j,s+1}-\tau_j)\big(f_{j,s+1}^{\mathrm{K}}+\Phi'_{j,s+1}I_{j,s+1}^{2}K_{j,s+1}^{-2}\big)+\lambda_{j,s+1}(1-\delta_j)\Big](1+r_s)^{-1}=\lambda_{js} \tag{B20}$$

$$\Big[(p_{j,s+1}-\tau_j)f_{j,s+1}^{\mathrm{H}}+\mu_{j,s+1}\Big](1+r_s)^{-1}=\mu_{js} \tag{B21}$$

where $f_{j,s+1}^{\mathrm{K}}\equiv\partial X_{j,s+1}/\partial K_{j,s+1}$, $f_{j,s+1}^{\mathrm{H}}\equiv\partial X_{j,s+1}/\partial H_{j,s+1}$, and $\Phi'_{js}\equiv\partial\Phi_{js}/\partial(I_{js}/K_{js})$. Eqs. (B18) and (B19) indicate that investment in physical capital or R&D services must proceed until the shadow value of incremental investment (λ or μ) just equals the price of the investment, net of subsidies or marginal adjustment costs, as applicable. Eqs. (B20) and (B21) define changes in shadow prices along the optimal path. The left-hand side in each equation is the marginal contribution to V of capital that is introduced next period, discounted to the present period. This must equal the shadow value of capital in the present period (right-hand side).

B.3.2.3. Output supplies and profit. In the **EA**, **EA**, **MI**, and **MN** industries, firm-value-maximizing output supplies are determined by the current capital stocks (given in the current period) and optimal intensities for the variable inputs. Substituting the optimal input intensities from Eq. (B12) into Eq. (B1) yields:

$$G_{jt}=\left(\frac{\alpha_{\mathrm{K}}}{1-\tilde{\alpha}_{jt}}\right)^{1/\rho_{\mathrm{G}j}}K_{jt} \tag{B22}$$

where

$$\tilde{\alpha}\equiv\alpha_{\mathrm{L}j}a_{\mathrm{L}jt}^{\rho_{\mathrm{G}j}}+\alpha_{\mathrm{E}j}a_{\mathrm{E}jt}^{\rho_{\mathrm{G}j}}+\alpha_{\mathrm{M}j}a_{\mathrm{M}jt}^{\rho_{\mathrm{G}j}} \tag{B23}$$

Given G_{jt} and H_{jt}, the level of output X_{jt} can be calculated using Eq. (B1).

In the **I**, **R**, and **C** industries, there are no fixed factors, and output supply is determined by aggregate demand for each good. Aggregate demand for new capital goods and R&D services are:

$$I_{\mathrm{AD}_t}=\sum_j I_{jt} \tag{B24}$$

$$R_{\mathrm{AD}_t}=\sum_j R_{jt} \tag{B25}$$

The input levels demanded by each firm are:

$$EC_{jt} = a_{\mathrm{EC}\,jt} a_{\mathrm{E}\,jt} G_{jt}$$
$$EA_{jt} = a_{\mathrm{EA}\,jt} a_{\mathrm{E}\,jt} G_{jt}$$
$$MI_{jt} = a_{\mathrm{MI}\,jt} a_{\mathrm{M}\,jt} G_{jt}$$
$$MN_{jt} = a_{\mathrm{MN}\,jt} a_{\mathrm{M}\,jt} G_{jt} \tag{B26}$$

Current gross profit to each firm is: [49]

$$\pi_{jt} = (p_{jt} - \tau_j)(X_{jt} - \Phi_{jt}) - p_{\mathrm{EC}\,t} EC_{jt} - p_{\mathrm{EA}\,t} EA_{jt} - p_{\mathrm{MI}\,t} MI_{jt} - p_{\mathrm{MN}\,t} MN_{jt} - p_{\mathrm{L}\,t} L_{jt} \tag{B27}$$

B.3.2.4. Household behavior. The maximization problem for the representative household is:

$$\max U_t = \sum_{s=t}^{\infty} (1+\omega)^{t-s} N_s \frac{1}{\rho_{\mathrm{U}}} C_s^{\rho_{\mathrm{U}}} \tag{B28}$$

and the household's wealth accumulation condition in each period is:

$$W_{\mathrm{F}t} - W_{\mathrm{F},t-1} = r_{t-1} W_{\mathrm{F},t-1} + Y_{\mathrm{L}\,t} + Y_{\mathrm{G}\,t} - p_{\mathrm{C}\,t} N_t C_t \tag{B29}$$

$W_{\mathrm{F}t}$, $Y_{\mathrm{L}\,t}$, and $Y_{\mathrm{G}\,t}$ are given by:

$$Y_{\mathrm{L}\,t} = p_{\mathrm{L}\,t} \sum_j L_{jt} \tag{B30}$$

$$Y_{\mathrm{G}\,t} = \sum_j \left[\tau_j (X_{jt} - \Phi_{jt}) - \upsilon_j p_{\mathrm{R}\,t} R_{jt} \right] \tag{B31}$$

$$W_{\mathrm{F}t} = \sum_j V_{jt} \tag{B32}$$

Differentiating the Lagrangean function for the household's constrained optimization problem yields the following first-order conditions:

$$C_s^{\rho_{\mathrm{U}}-1} = \xi_s p_{\mathrm{C}\,s} (1+\omega)^{s-1} \tag{B33}$$
$$\xi_s = \xi_{s+1}(1+r_s) \tag{B34}$$

where ξ_s is the shadow value of household wealth evaluated at time s. Aggregate household flow income (excluding capital gains) and aggregate flow saving are:

$$Y_t = \sum_j \pi_{jt} + Y_{\mathrm{L}\,t} + Y_{\mathrm{G}\,t} \tag{B35}$$

$$S_t = Y_t - p_{\mathrm{C}\,t} N_t C_t \tag{B36}$$

[49] The sum of firms' profits is not equal to household capital income because it excludes capital gains. Φ_{jt}, L_{jt}, I_{jt}, and R_{jt} are zero for $j=$ **I**, **R**, or **C**. We assume all gross profits are returned to households; there are no retained earnings.

B.3.2.5. Spillover knowledge. Spillover knowledge accumulates according to:

$$\overline{H}_{j,t+1} = \overline{H}_{jt} + \beta \overline{R}_{jt} \tag{B37}$$

$\overline{H}_{j1}$ is arbitrarily set to 1. The production scale factor γ_{jt} is equal to $\overline{H}_{jt}$, for all j and t.

B.3.2.6. Aggregate demands, aggregate supplies, and equilibrium conditions. Aggregate demands for intermediate inputs and for labor are:

$$EC_{\mathrm{AD}_t} = \sum_j EC_{jt} \tag{B38}$$

$$EA_{\mathrm{AD}_t} = \sum_j EA_{jt} \tag{B39}$$

$$MI_{\mathrm{AD}_t} = \sum_j MI_{jt} \tag{B40}$$

$$MN_{\mathrm{AD}_t} = \sum_j MN_{jt} \tag{B41}$$

$$L_{\mathrm{AD}_t} = \sum_j L_{jt} \tag{B42}$$

Aggregate labor supply is proportional to population:

$$L_{\mathrm{AS}_t} = \alpha_{\mathrm{N}} N_t \tag{B43}$$

The conditions for market-clearing in each period are:

$$EC_{\mathrm{AD}_t} = X_{\mathrm{EC}t} \tag{B44}$$

$$EA_{\mathrm{AD}_t} = X_{\mathrm{EA}t} \tag{B45}$$

$$MI_{\mathrm{AD}_t} = X_{\mathrm{MI}t} \tag{B46}$$

$$MN_{\mathrm{AD}_t} = X_{\mathrm{MN}t} \tag{B47}$$

$$L_{\mathrm{AD}_t} = L_{\mathrm{AS}_t} \tag{B48}$$

$$\sum_j \left[p_{\mathrm{I}t} I_{jt} + p_{\mathrm{R}t} (1 - v_{jt}) R_{jt} \right] = S_t \tag{B49}$$

Eqs. (B44), (B45), (B46) and (B47) require that the aggregate demand for each intermediate input equal its supply. Eq. (B48) requires that aggregate labor demand equal its supply. Eq. (B49) requires that firms' demands for loanable funds equal the value of funds supplied by household saving. By Walras's law, one of the market-clearing conditions is redundant. We employ Eqs. (B44), (B45), (B46), (B47) and (B49) to solve for the equilibrium values of p_{EC}, p_{EA}, p_{MI}, p_{MN}, and r in each period. The price of labor (p_{L}) is the numeraire.

B.3.2.7. Solving for the perfect foresight equilibrium. To solve for the perfect foresight equilibrium, we first solve the model under steady-state constraints to obtain the steady-state values for λ_j, μ_j, and ξ ($j=$ **EC**, **EA**, **MI**, and **M**). We then specify *posited dynamic variables* that incorporate expectations about the future. Using these variables, we solve the model forward from period 1 to T, where T represents the last period simulated. We then compare the values of the posited dynamic variables with values of *derived dynamic variables* that result from the simulation. If posited and derived values do not match, we specify a new set of posited dynamic variables and solve the model forward again. We repeat this procedure until posited and derived values match (within 0.01%).

More specifically, we define the following posited dynamic variables:

$$\psi^p_{\mathrm{K}js} = (p_{js} - \tau_j)\left(f^{\mathrm{K}}_{js} + \Phi'_{js} I^2_{js} K^{-2}_{js}\right) + \lambda_{js}(1-\delta_j) \tag{B50}$$

$$\psi^p_{\mathrm{H}js} = (p_{js} - \tau_j) f^{\mathrm{H}}_{js} + \mu_{js} \tag{B51}$$

$$\psi^p_{\mathrm{W}s} = \xi_s \tag{B52}$$

for $s=2, 3, \dots, T$. For $s=T+1$, we impose steady-state values for the dynamic variables. (The steady-state solution of the model yields values for all of the right-hand side elements in Eqs. (B50), (B51) and (B52) in the steady state.) For $s=2, 3, \dots, T$, the initial value for the positive dynamic variables are set arbitrarily. For $s=2, 3, \dots, T$, the initial values for the posited dynamic variables must be set arbitrarily. After establishing initial paths for the posited dynamic variables, we solve the model forward. The posited dynamic variables are used to generate values for the variables λ_j, μ_j, and ξ in periods 1 through T. From Eqs. (B20), (B21) and (B34):

$$\lambda_{js} = \varphi^p_{\mathrm{K}j,s+1}(1+r_s)^{-1} \tag{B53}$$

$$\mu_{js} = \varphi^p_{\mathrm{H}j,s+1}(1+r_s)^{-1} \tag{B54}$$

$$\xi_s = \varphi_{\mathrm{W},s+1}(1+r_s) \tag{B55}$$

The resulting values for λ_{js}, μ_{js}, and ξ_s generate levels of investment and consumption, based on Eqs. (B18), (B19) and (B33). After solving the model forward, we calculate the *derived* dynamic variables $\psi_{\mathrm{K}js}$, $\psi_{\mathrm{H}js}$, and $\psi_{\mathrm{W}s}$, for $s=1, 2, \dots, T$, using Eqs. (B20), (B21) and (B34) and the results from the forward solution of the model. If posited and derived values do not match within required accuracy, we update the path of posited dynamic variables according to:

$$\varphi^{p(k+1)}_{\mathrm{K}js} = \zeta\varphi^{(k)}_{\mathrm{K}js} + (1-\zeta)\,\varphi^{p(k)}_{\mathrm{K}js} \tag{B56}$$

$$\varphi^{p(k+1)}_{\mathrm{H}js} = \zeta\varphi^{(k)}_{\mathrm{H}js} + (1-\zeta)\,\varphi^{p(k)}_{\mathrm{H}js} \tag{B57}$$

$$\varphi^{p(k+1)}_{\mathrm{W}s} = \zeta\varphi^{(k)}_{\mathrm{W}s} + (1-\zeta)\,\varphi^{p(k)}_{\mathrm{W}s} \tag{B58}$$

where k is the iteration number and ζ is a constant between 0 and 1. We continue this procedure until posited and derived dynamic variables match. When they correspond, the equations of motion for the shadow values λ_{js}, μ_{js}, and ξ_s (i.e., Eqs. (B18), (B19) and (B33)) are satisfied by the model's results. Since the path of each shadow value culminates in the steady state value, the levels as well as changes meet the requirements of the intertemporal solution of the model.

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